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(TITLE UNCLASSIFIED) EXPERIMENTAL INVESTIGATION OF PREPACKAGED HYBRID PROPULSION SYSTEMS

C. W. VICKLAND

UNITED TECHNOLOGY CENTER

TECHNICAL REPORT AFRPL-TR-66-268
FEBRUARY 1967

Group 4

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AIR FORCE ROCKET PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND, UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

UTC 2141-ITR1

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United Technology Center DIVISION OF UNITED AIRCRAFT CORPORATION

1 March 1967

ADP-241-67-F

Air Force Rocket Propulsion Laboratory
Edwards, California 93523

Attention: RPRE

Subject: Interim Technical Report, AFRPL-TR-66-268
UTC 2141-ITR1

Reference: Contract AF 04(611)-10789, DD Form 1423,
Line Item No. 13

Gentlemen:

United Technology Center submits one (1) copy of the subject report in accordance with the referenced contract.

This report covers the period 1 April 1965 through 31 January 1966.

Very truly yours,

UNITED TECHNOLOGY CENTER
A Division of United Aircraft Corporation

A. D. Parker, Manager
Contract Management

ADP:btu

Enclosure

cc: AFFTC, Edwards AFB, Calif. 93523
Attn: FTMKR-4 (w/o encl.)
AFPRO, UTC, Sunnyvale, Calif. 94088
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FOREWORD

(U) The work performed under this project is in response to requirements of AFFTC Project 3058, Program Structure No. 750G, BPSN 623148. The Air Force Program Monitor is Lt. William Spangler, Air Force Rocket Propulsion Laboratory, Research and Technology Division, Edwards, California.

(U) The present report is the technical summary of work conducted under Contract AF 04(611)-10789 under which United Technology Center (UTC) is conducting an experimental investigation of prepackaged hybrid propellant systems.

(U) This report covers experimental work conducted at UTC's Sunnyvale, California, research laboratories and UTC's San Jose, California, processing laboratories during the period 1 April 1965 through 31 January 1966. The following professional workers made significant contributions to progress on this program:

L. K. Asaoka	J. H. Murray
R. Brogan	M. W. Stark
R. W. Ebeling	K. L. Tacke
G. A. Kinkel	D. A. Talaska
R. A. Maraschin	E. D. Vessel
D. R. Matthews	J. Wing

(U) This report contains classified information extracted from "Experimental Investigation of Prepackaged Hybrid Propulsion Systems (U)," UTC 2141-QPR1, 15 August 1965, and UTC 2141-QPR2, November 1965. CONFIDENTIAL, Group 4.

(U) This technical report has been reviewed and is approved.

Approving Authority
is Lt. William Spangler

ABSTRACT

(U) An applied research and development program is being conducted on prepackaged hybrid propellant systems suitable for application to advanced tactical missile requirements.

(U) An 18-in.-diameter flight configuration hybrid motor has been designed, fabricated, and tested in three motor firings. A high density, high specific impulse, hybrid propellant combination has been formulated; and a fuel grain has been developed which will provide nearly constant fuel flow rate and will permit nearly complete fuel utilization. Dual-thrust injectors have been developed and successfully tested. A simple thrust control system has been designed, which will control the motor thrust at two levels and will permit multiple starts at either thrust level.

(U) The results of the program indicate that high density hybrid propulsion systems are feasible for application to advanced tactical missiles.

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ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

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ABBREVIATIONS AND SYMBOLS

O/F	gravimetric mixture ratio of oxidizer to fuel
ρ_b	propellant bulk density, gm/cc
ρ_b^{175}	propellant bulk density at 175° F gm/cc
I_{sp}	specific impulse, sec
ρI_{sp}	density impulse, gm-sec/cc
g	gravitational constant, ft/sec^2
ΔV	vehicle burnout velocity, ft/sec
K	staging parameter, K = M/V
M	vehicle burnout weight
V	propellant volume
ρ	density
$\dot{r}$	fuel regression rate, in./sec
a	proportionality constant
P_c	chamber pressure, psi
m	exponent expressing regression rate dependent on chamber pressure
G_o	oxidizer mass flux = $\frac{W_{ox}}{A_p}$, lb/sec-in.^{2}
$\dot{W}_{ox}$	oxidizer flow rate, lb/sec
A_p	total cross-sectional area of fuel grain port (varies with burning time), in.^{2}

TAZ	triaminoguanidine azide
THA	triaminoguanidine azide — hydrazine azide
TFTA	tetraformaltrisazine
B	boron
Al	aluminum
AP	ammonium perchlorate
QX/DER	3812 QX binder with DER curative
R-binder	hydrocarbon binder
PBD	polybutadiene binder
$\dot{W}_f$	fuel flow rate, lb/sec
ρ_f	fuel density, lb/in.^{3}
P_b	perimeter dimension of burning fuel port, for example = πD of cylindrical fuel grain
L	length of fuel grain, in.

SECTION I

INTRODUCTION

(U) This report is a summary of the work accomplished to date on Contract AF 04(611)-10789. Under this contract, UTC has been conducting an applied research and development program on prepackaged hybrid propellant systems suitable for application to advanced tactical missile requirements.

(U) The program consists of an evaluation of candidate fuel systems and ingredients for which studies were initiated under Contract AF 04(611)-8516, development of flight-configuration thrust chamber components including injectors and an oxidizer flow-control system, and demonstration testing of complete flight configuration hybrid thrust chamber assemblies (TCA).

(U) The scope of the program was to develop, in a 9-month effort, a flight configuration hybrid thrust chamber assembly which is capable of delivering approximately 200,000 lb-sec of impulse; the impulse to be deliverable from storable prepackaged propellants at two thrust levels, 5,000-lb (boost thrust) and 2,500-lb (sustain thrust) with up to two motor restarts after short coasting periods.

(U) The program has resulted in the development of all flight configuration TCA components, including injectors, valves, fuel grain shape, nozzle and thrust chamber. Numerous subscale motor tests and three full-scale motor tests have been conducted with the components and thrust chambers. These tests indicate that a high density hybrid propulsion system is feasible for application to advanced tactical missiles.

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SECTION II

SUMMARY

(U) An 18-in.-diameter hybrid thrust chamber assembly has been developed and test fired for durations up to 15 sec. The TCA is designed for 1,000 psi chamber pressure during boost thrust (5,000 lb) operation and 500 psi during sustain thrust operation. The thrust chamber assembly includes injectors, valves, 240 lb of fuel, and the thrust chamber itself. The motor will be capable of providing 200,000 lb-sec impulse at either constant thrust or dual thrust duty cycles which include multiple restarts.

(C) The program has resulted in the development of a castable fuel system capable of on-off operation which contains 30% tetraformaltrisazine (TFTA), 5% boron, 30% ammonium perchlorate (AP), and 35% binder. The fuel has a theoretical specific impulse of 284 sec and a density impulse of 453 gm-sec/cc when used with an oxidizer of ClF_5. The propellant system has a growth potential to 295 sec specific impulse and 503 gm-sec/cc density impulse when processing and combustion characteristics are simultaneously resolved.

(C) A unique multiple port fuel grain shape has been developed and successfully tested in subscale and full-scale motor firings which provides 92% cross-sectional loading and only 6.7% sliver. The grain shape, when used with the selected fuel, will deliver essentially constant fuel flow rates and will thereby provide a constant mixture ratio while permitting almost complete fuel utilization. Seven of the full-scale fuel grains have been cast, each weighing over 240 lb.

(C) The propellant studies which included 61 5.0-in. motor tests, 48 3.5-in. motor tests, 79 laboratory research motor tests, and 34 optical bomb tests which resulted in the successful development of three other castable fuel systems in addition to the ones previously mentioned. All four fuels contain TFTA, boron, AP, and binder and all may be suited for advanced tactical missiles. The highest performance fuel has a theoretical specific impulse of 295 sec and a density impulse of 503 gm-sec/cc; however, the combustion characteristics of this fuel limit its operation to single or multiple thrust duty cycles without on-off operation.

(U) A thrust control system was developed which will permit operation of the TCA at either thrust level while maintaining essentially constant mixture ratio. The thrust control system includes a dual element solenoid valve, six dual flow injectors, and a single aft injector. The flight configuration valve, which weighs 5 lb, was fabricated and bench tested in preparation for full-scale motor tests, and the injectors have all been successfully tested in subscale and full-scale tests with durations up to 17 sec. The unique injector design permits two flow rates to be injected for dual thrust operation while maintaining an effective spray pattern. In addition, it provides positive shutoff at the injector face, thus preventing posttest contamination of the feed system with fuel rich vapors.

(U) Development of each of the components comprising the full-scale thrust chamber assembly has progressed to the point by which each has demonstrated performance consistent with the requirements of advanced tactical missiles.

SECTION III

PROPELLANT SELECTION

(U) Hybrid propellants, in order to be suitable for application to tactical missile systems, must deliver a relatively high specific impulse, and possess an adequate high temperature bulk density to meet both weight and volume limitations. The fuel must not sustain combustion on termination of oxidizer flow, it on-off operation is to be achieved. In addition, the propellants should provide smooth and reproducible hypergolic ignition and efficient combustion, and should have exhaust products which produce favorable radar characteristics.

(C) Fuels consisting of TAZ, boron, AP, and binder were originally selected for use with ClF_5, BrF_5, and ClO_3F oxidizers for the development of a propellant system meeting the above requirements. These fuels were selected for development and for demonstration in full-scale motors because calculations had shown that they could provide specific impulse values of 295 sec and density impulse values of 503 gm-sec/cc. Other fuels are available which exceed the selected combinations in performance but were not considered because of other disadvantages. For an example, higher specific impulse (309 sec) is available with lithium-containing castable hybrid fuels (25% Li/10% LiH/65% binder), but the lithium fuel has relatively low density (0.8 g/cc) and unfavorable exhaust radar properties. Extremely high density impulse values (540 gm-sec/cc) can be obtained using high boron loading and BrF_5 oxidizer, but they have correspondingly low specific impulse values.

(U) System design studies were conducted with a view to the selection of those propellant characteristics which yield maximum vehicle performance, consistent with weight and volume restrictions of a typical missile system. The studies were intended to determine the significance of specific impulse versus density impulse with respect to overall vehicle performance.

(U) The propellant formulations found to offer greatest potential are those which have the highest specific impulse while exhibiting a bulk propellant density sufficient to meet the weight and volume limitations imposed by the mission. Increasing the bulk density of a high specific impulse system after the vehicle weight limitation is reached does not produce significant returns in vehicle performance.

(C) The conclusions reached from this study indicated that the oxidizers selected should be limited to those which primarily produce high specific impulse but with the highest possible density impulse. Therefore, the criteria favors the use of ClF_5 with its generally higher specific impulse rather than BrF_5 with its higher density impulse but generally lower specific impulse. The study indicates that ClF_5/ClO_3F mixtures offer increased vehicle performance over ClF_5 when the oxidizer temperature does not exceed 175° F. However, for systems which operate above that temperature, the reduced bulk density of ClO_3F containing oxidizers severely diminish vehicle performance. Up to 10% ClO_3F may be used in systems which operate at 175° F, but if oxidizer temperatures up to 195° F are anticipated, only ClF_5 should be considered. The bulk density of propellant systems using ClO_3F can be improved upon by the addition of BrF_5 to the blend, but then the reduction in specific impulse results in vehicle performance which is no better than that obtained using pure ClF_5 as oxidizer.

(U) The study also indicates that no gain in vehicle performance would be obtained by operating with mixture ratios (O/F) higher than stoichiometric mixture ratio.

1. ANALYTICAL MODEL

(C) In order to determine the criteria for propellant selection, an analytical model of a typical advanced tactical missile was developed. The model, which is both weight and volume limited, is shown schematically in figure 1. It has the following characteristics:

Overall diameter	18.25 in.
Overall length	81.0 in.
Maximum chamber pressure	2,000 psia
Overall weight	900 lb
Nozzle area ratio	8:1
Boost thrust	5,000 lb
Sustain thrust	2,500 lb
Thrust cycle	Boost-coast-sustain-coast-boost.

(C) Forty-two typical fuel formulations were selected for this study. The ingredients in table I were used in combinations which took into consideration propellant processability, propellant density, and performance. These formulations are shown in table II. For the purpose of this study, these propellant systems are well characterized by the curves of figure 2. The valves of I_{sp} listed in table II would be approximately 8-10 sec lower if ClF_3 were substituted for ClF_5.

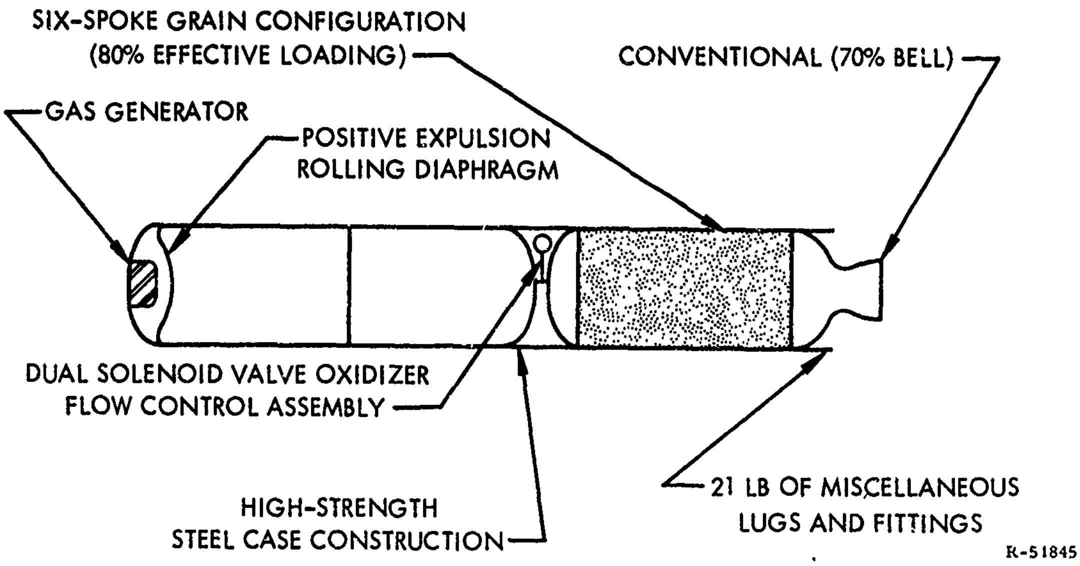

Figure 1. (U) Propulsion System Analytical Model

TABLE I

(U) PROPELLANT INGREDIENTS

Ingredient	Molecular Weight	Heat of Formation ΔH_f kcal/mole
TAZ	147.16	+105.7
TFTA	144.19	+86.2
Al	26.97	0
B	10.8	0
AP	117.5	-70.7
PBD	54.09	+7.4
QX 3812	102.0	-92.2
DER	16.2	-11.2
ClF_5	130.5	-58.0
BrF_5	174.92	-109
ClO_3F	102.46	-10.1

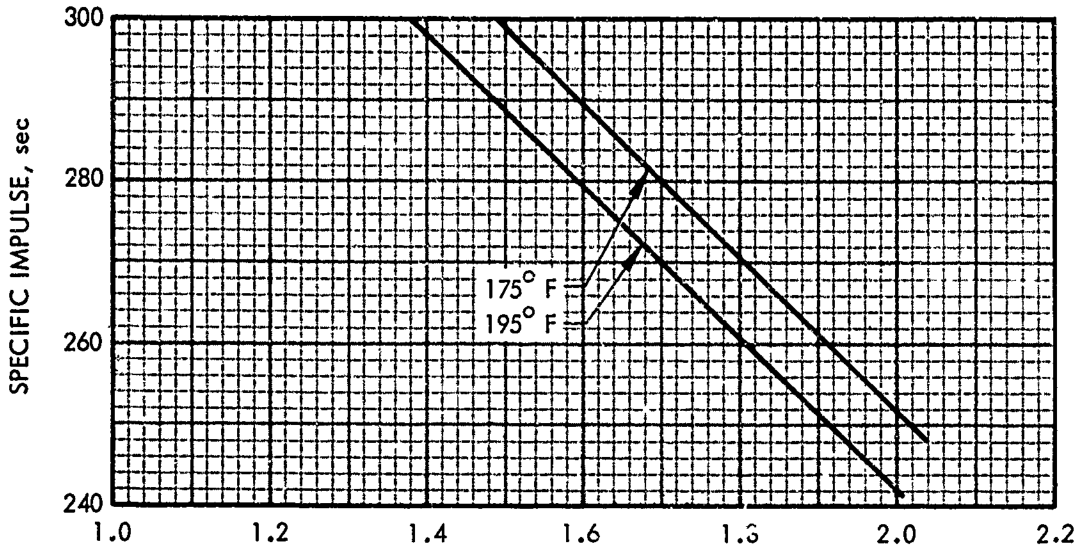

Figure 2. (U) Specific Impulse and Bulk Density of Available Propellant Systems

(C) Since the final propellant to be selected may be required to withstand a temperature environment in excess of 165° F, two temperature limits (175° and 195° F) have been arbitrarily selected for density analysis. Although these linear relationships result in a simplfied analysis, study of formulations containing the ingredients being considered indicate that systems could be formulated to meet (or closely approach) any point represented by the lines in figure 2. At the same time, it has been found to be quite difficult to formulate a system by conventional processing techniques that significantly exceeds the performance represented by these lines.

(U) As a preliminary step in the analysis of this model, the minimum propellant bulk density required to meet the weight and volume limitations was calculated as a function of mixture ratio and motor mass fraction and is presented in figures 3 and 4. Propellant formulations, with a density greater than the indicated minimum, result in vehicles occupying a volume less than the allowable maximum; whereas, formulations with lesser density result in vehicles weighing less than the allowable maximum.

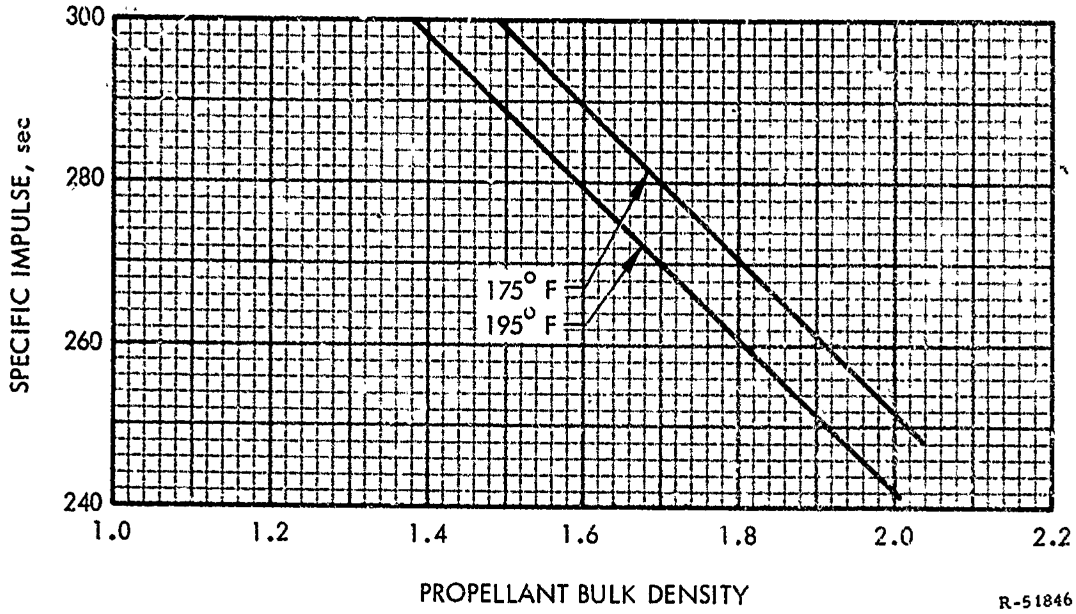

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TABLE II

(U) CANDIDATE PROPELLANT SYSTEMS FOR TACTICAL MISSILE PROPULSION SYSTEM

Fuel							Oxidizer						
TAZ	TFTA	Al	B	AP	PBD	QX-DER	ClF_5	ClO_3F	BrF_5	I_{sp}	O/F	ρb^{175}	ρb^{195}
-	45	-	20	-	-	35	75	25	-	295	3.5	1.37	1.305
-	45	20	-	-	-	35	70	30	-	288	2.5	1.35	1.280
40	-	-	15	25	20	-	100	-	-	291	2.2	1.53	1.50
15	-	-	40	25	20	-	100	-	-	289	2.6	1.57	1.54
30	-	-	25	25	20	-	100	-	-	285	3.5	1.54	1.51
50	-	-	-	-	50	-	50	50	-	290	2.7	1.245	1.15
-	50	-	-	-	50	-	50	50	-	288	3.1	1.23	1.138
25	-	-	30	25	-	20	100	-	-	291	3.0	1.56	1.528
29	-	-	25	26	-	20	100	-	-	293	2.6	1.555	1.525
33	-	-	20	27	-	20	100	-	-	294	2.3	1.546	1.515
37	-	-	15	28	-	20	100	-	-	295	2.0	1.54	1.513
41	-	-	10	25	-	20	100	-	-	295	1.75	1.545	1.52
30	-	-	25	25	20	-	100	-	-	289	2.6	1.55	1.525
35	-	-	30	15	20	-	100	-	-	287	3.0	1.540	1.510
25	-	-	20	35	20	-	100	-	-	292	2.5	1.548	1.519
20	-	-	15	45	20	-	100	-	-	294	2.0	1.553	1.526
-	16	-	30	34	-	20	100	-	-	290	3.0	1.563	1.53
-	19	-	25	36	-	20	100	-	-	292	2.7	1.56	1.53
-	22	-	20	38	-	20	100	-	-	292	2.4	1.55	1.52
-	25	-	15	40	-	20	100	-	-	293	2.1	1.541	1.515
-	27	-	10	43	-	20	100	-	-	293	1.7	1.535	1.510
-	22	20	-	38	-	20	100	-	-	289	1.4	1.565	1.54
35	-	-	20	15	-	30	90	10	-	293	2.8	1.467	1.425
35	-	-	20	15	-	30	80	20	-	293	2.5	1.43	1.36
-	35	20	-	15	-	30	80	20	-	288	2.2	1.42	1.36
-	35	20	-	15	-	30	90	10	-	285	2.0	1.451	1.414
-	35	20	-	15	-	30	100	-	-	282	1.8	1.50	1.47
-	55	-	25	-	-	20	78	22	-	295	3.6	1.406	1.33
-	60	-	20	-	-	20	75	25	-	296	3.3	1.38	1.305
-	65	-	15	-	-	20	72	28	-	296	3.1	1.362	1.285
35	-	-	30	15	20	-	50	-	50	266	3.3	1.758	1.727
35	-	-	30	15	20	-	-	-	100	242	4.0	2.078	2.052
40	-	-	40	-	20	-	-	20	80	256	4.8	1.797	1.702
40	-	-	40	-	20	-	20	20	60	266	4.4	1.687	1.600
40	-	-	40	-	20	-	40	20	40	276	4.0	1.594	1.513
40	-	-	40	-	20	-	60	20	20	284	3.8	1.513	1.438
40	-	-	40	-	20	-	80	20	-	293	3.6	1.444	1.370
-	-	-	55	30	15	-	-	-	100	240	5.3	2.196	2.166
-	-	-	55	30	15	-	25	-	75	253	4.5	1.997	1.964
-	-	-	55	30	15	-	50	-	50	264	4.2	1.840	1.804
-	-	-	55	30	15	-	75	-	25	275	3.9	1.708	1.672
-	-	-	55	30	15	-	100	-	-	285	3.5	1.600	1.567
-	30	-	5	30	35	-	100	-	-	284	2.0	1.458	1.432

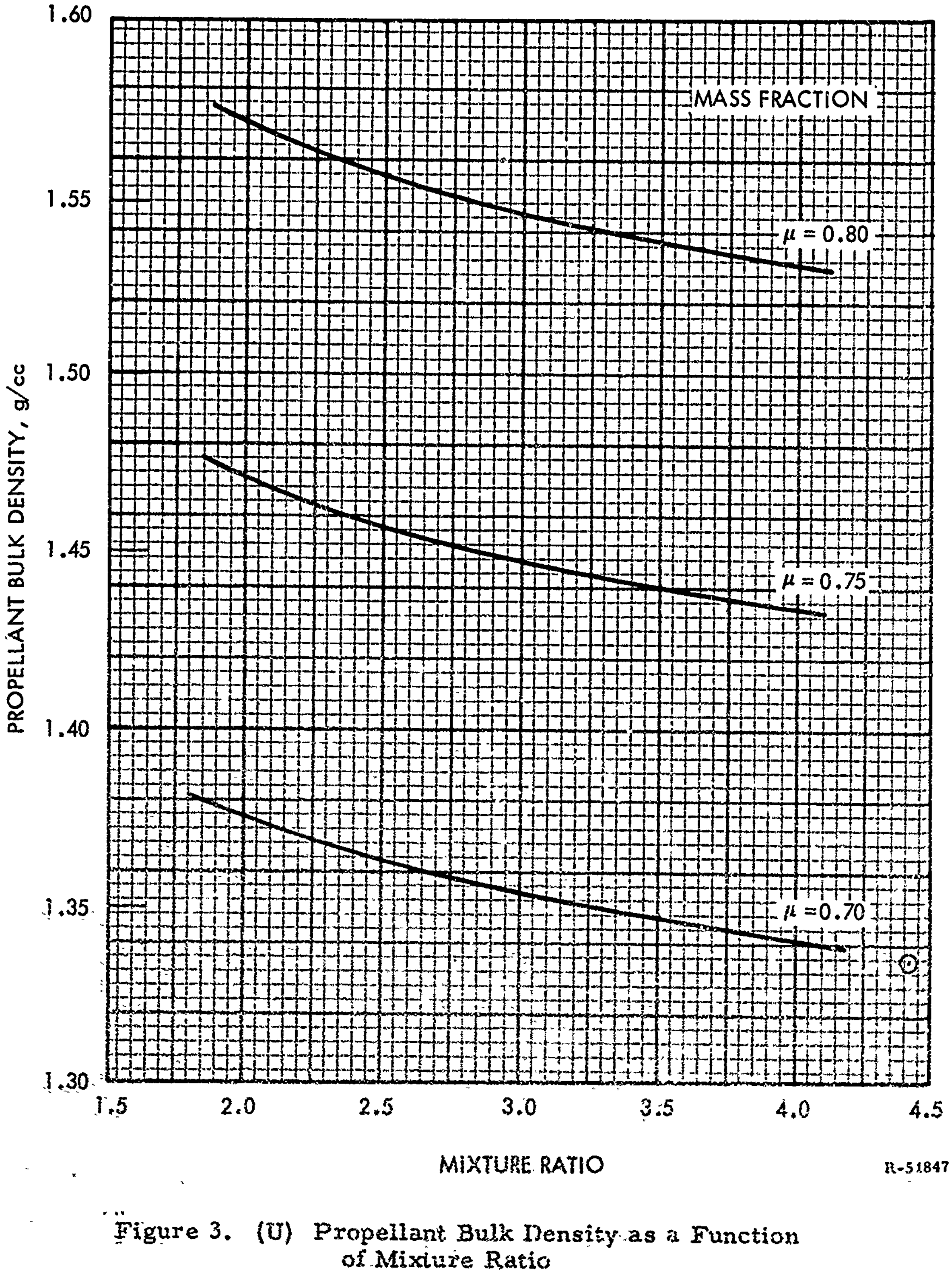

Figure 3. (U) Propellant Bulk Density as a Function of Mixture Ratio

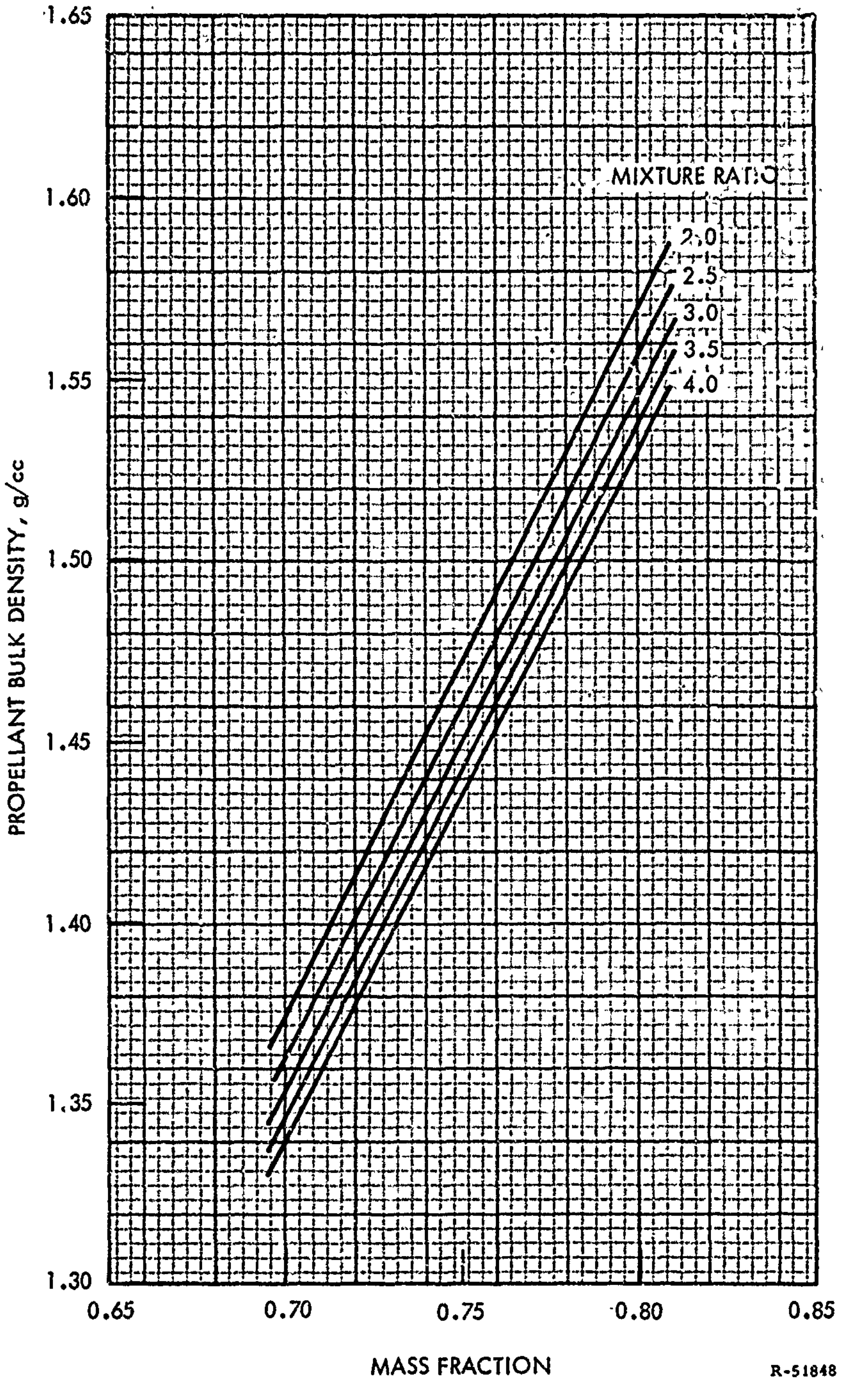

Figure 4. (U) Propellant Bulk Density as a Function of Mass Fraction

(U) The criteria for propellant selection are necessarily tied to the requirements of the vehicle mission. However, since a precise mission is not defined, calculation of theoretical burnout velocity (with due consideration to vehicle weight and volume limits) provides a basis for selection of propellant characteristics which is superior to attaching arbitrary significance to specific impulse or combinations of specific and density impulse.

(C) In an attempt to determine the significant criteria for propellant selection, the burnout velocity equation

$$\Delta v = I_{sp} \cdot g \cdot \ln (1 + \rho/K)$$

has been used, where K is the design dependent variable (often referred to as the staging ratio) and is defined as M/V, where M is the vehicle burnout weight, and V, the propellant volume. Using the propulsion unit model referred to above, several series of propulsion units have been designed with specific impulse and density values consistent with the curves of figure 2. The conclusions reached from this analysis are typified by the series designed to a mixture ratio of 3.0 and payload weight of 500 lb which is developed below.

(U) The staging ratio for this series, calculated as a function of propellant bulk density, is presented in figure 5. The discontinuity observed in this curve results from the volume and weight limitations imposed by the design criteria. Staging ratios, corresponding to propellant bulk densities below the point of discontinuity, represent designs which are constrained by volume limitations. Those above the point are constrained by weight limitations. When the appropriate values of propellant density, specific impulse, and design staging ratio are used to calculate the burnout velocity parameter, optimized velocity values are achieved as indicated in figure 6. It is evident that the optimum burnout velocity occurs at a propellant bulk density corresponding to the point of discontinuity in figure 5.

(U) It may be concluded, therefore, that the propellant bulk density should be at least high enough to permit the loading of enough propellant to meet the weight limitation, (i.e., bulk density of 1.47) when using the entire allowable volume. Although desirable, an increase in density above this minimum value has far less influence on performance and should not normally be made at the expense of specific impulse. Almost all propellants under consideration possess bulk densities in excess of 1.45.

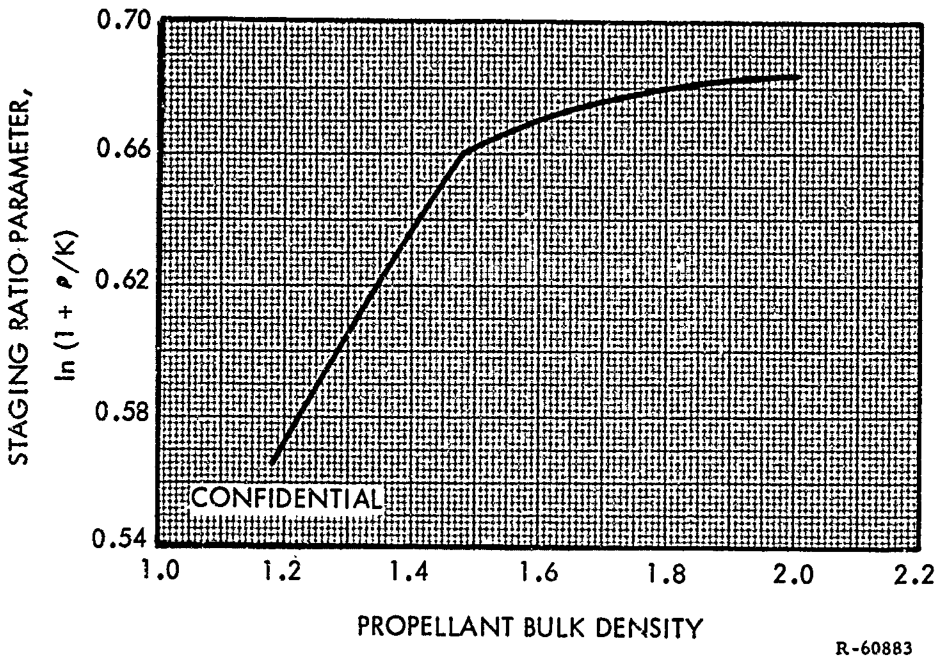

Figure 5. (U) Staging Ratio as a Function of Propellant Bulk Density

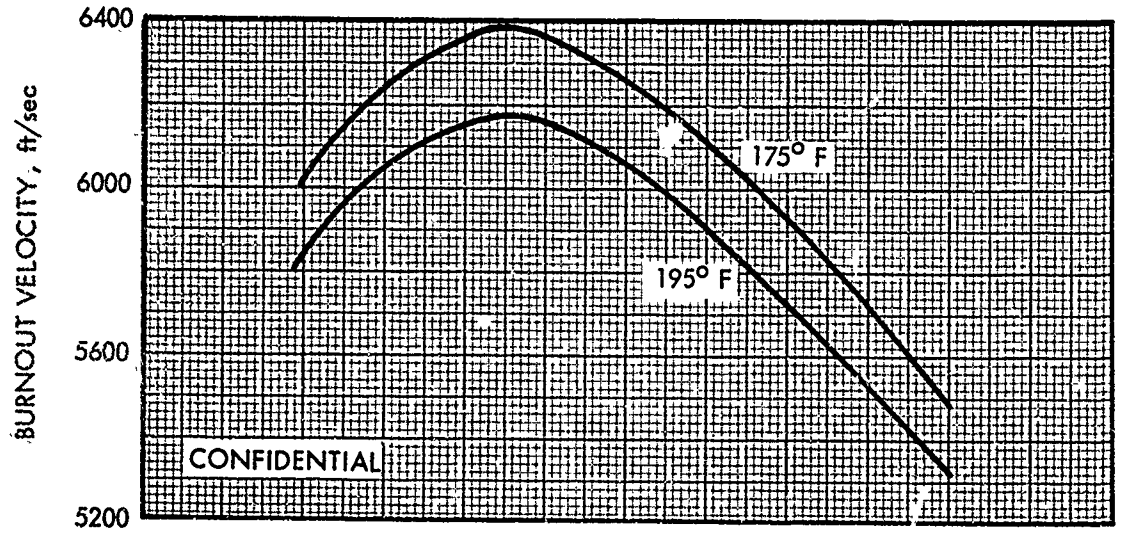

Figure 6. (U) Burnout Velocity as a Function of Propellant Bulk Density

(U) The mixture ratios listed in table II correspond to the optimum specific impulse value for each formulation. An analysis has been made to determine whether a performance advantage could be had by operating off the optimum specific impulse mixture ratio. In order to accomplish this objective, an effective propellant bulk density parameter was developed which takes into account fuel grain volume loading, slivers, liner, and oxidizer tank gas generator effects, as well as relative densities of the fuel and oxidizer. It was found that the variation of this parameter with mixture ratio is very small, and that when these values are multiplied by the appropriate specific impulse values, the maximum effective propellant bulk density impulse occurs at a mixture ratio corresponding to the maximum specific impulse mixture ratio. This means that even for the most critical of volume-limited systems, the optimum design mixture ratio is the optimum specific impulse mixture ratio. It should be noted, however, that this conclusion might not be valid for a system with oxidizer and fuel densities greatly different from those considered in this analysis.

2. PROPELLANT SELECTION CRITERIA

(U) The selection of a fuel formulation containing TFTA or TAZ, boron or aluminum, AP, and binder is guided by the processability of propellant blends and the relative cost of ingredients in addition to performance and propellant bulk density. Obviously, if a maximum performance blend of the igredients were processable and resulted in a high density fuel which would not sustain combusion on termination of oxidizer flow,then no further consideration of the relative merits of each ingredient would be needed and the maximum performance blend would be formulated. However, such is not the case and relative merits and limitations of each ingredient must be weighed while reviewing the overall vehicle requirements. With a knowledge of these merits and limitations, the reader will be assisted in following the developmental effort described in section IV of this document.

(U) The primary ingredient of any fuel system is its binder, which is generally high in carbon content but may vary in content of hydrogen, nitrogen, and oxygen. Of interest in the selection of binder is the quantity of oxygen from oxidizer of other fuel sources which is required to consume carbon and produce high performance levels.

(C) Boron is the principal additive to the fuel because of its high performance and density advantages when used with halogen oxidizers. Aluminum could be used as an alternate to boron but with some performance decrease.

(C) High nitrogen additives such as TAZ and TFTA have a dual purpose in hybrid fuel formulations. First they provide a means of maintaining high performance where boron content is limited by processing or combustion characteristics by providing working gas while minimizing increase in carbon content. Secondly, they provide a means of augmenting hybrid fuel regression rate; apparently as a result of their high energy release on decomposing. Their density is less that of the metal additive, and, therefore, they tend to contribute to a reduction in propellant bulk density.

(C) Ammonium perchlorate also has a dual purpose in the formulations. Its primary purpose is to provide oxygen to the combusion process in order to achieve high performance levels. Ammonium Perchlorate significantly augments the regression rate of hybrid fuel formulations. In addition, its relatively high density makes it extremely desirable to be included in the formulation. The only limitation on the use of AP is its tendency to cause sustained combustion on termination of oxidizer flow, thus eliminating on-off operation. The maximum AP loading level allowable to produce non-sustaining fuel blend is affected by AP particle size, boron content, and motor design, but it may be as high as 40% of the fuel.

(C) In order to establish general guidelines for the selection of high density, high specific impulse propellants, ternary plots of the fuels were generated using the hypothetical propellant formulations listed in table II. Figures 7 and 8 show formulation diagrams for TAZ, B, AP, binder and TFTA, B, AP, binder systems. The ternary diagrams include only the fuel additives representing 75% of the fuel blend, the binder content having been held to an approximate practical limit of 25%.

(C) Due to the relatively low density of the nitrogen additives and binder, the concentrations of these ingredients should be limited. Consequently, less desirable formulations lie outside the indicated areas (corresponding to theoretical fuel densities less than approximately 1.45 g/cc).

(C) The carbon monoxide stoichiometry lines shown in the diagrams indicate conditions wherein sufficient oxygen is provided by the AP to oxidize the carbon present in the nitrogen additives and binder, assuming ClF_5 as the liquid oxidizer. It is generally undesirable to formulate fuels with an AP level in excess of that required for stoichiometry because the mixture ratio tends to decrease. Formulations with a relatively high mixture ratio are desirable because they permit more effective volume utilization as was indicated in figure 3. The reduced required bulk occurs as a result of better volumetric packaging of the liquid oxidizer. At the same time, it is not desirable to reduce the AP level too far below stoichiometric, because the specific impulse tends to decrease significantly as the formulations become oxygen deficient.

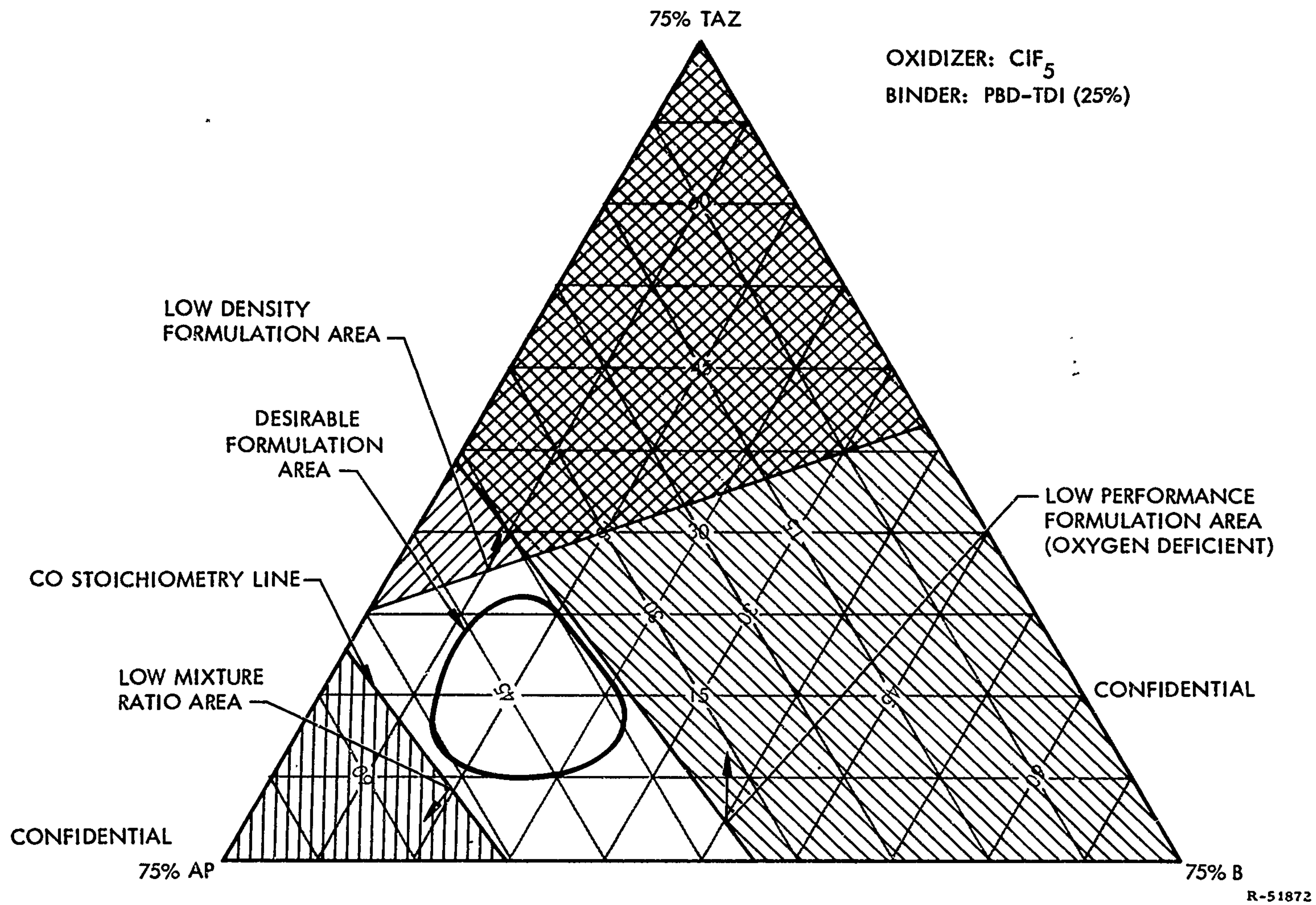

Figure 7. (U) Effect of Composition on the TAZ/B/AP/Binder System

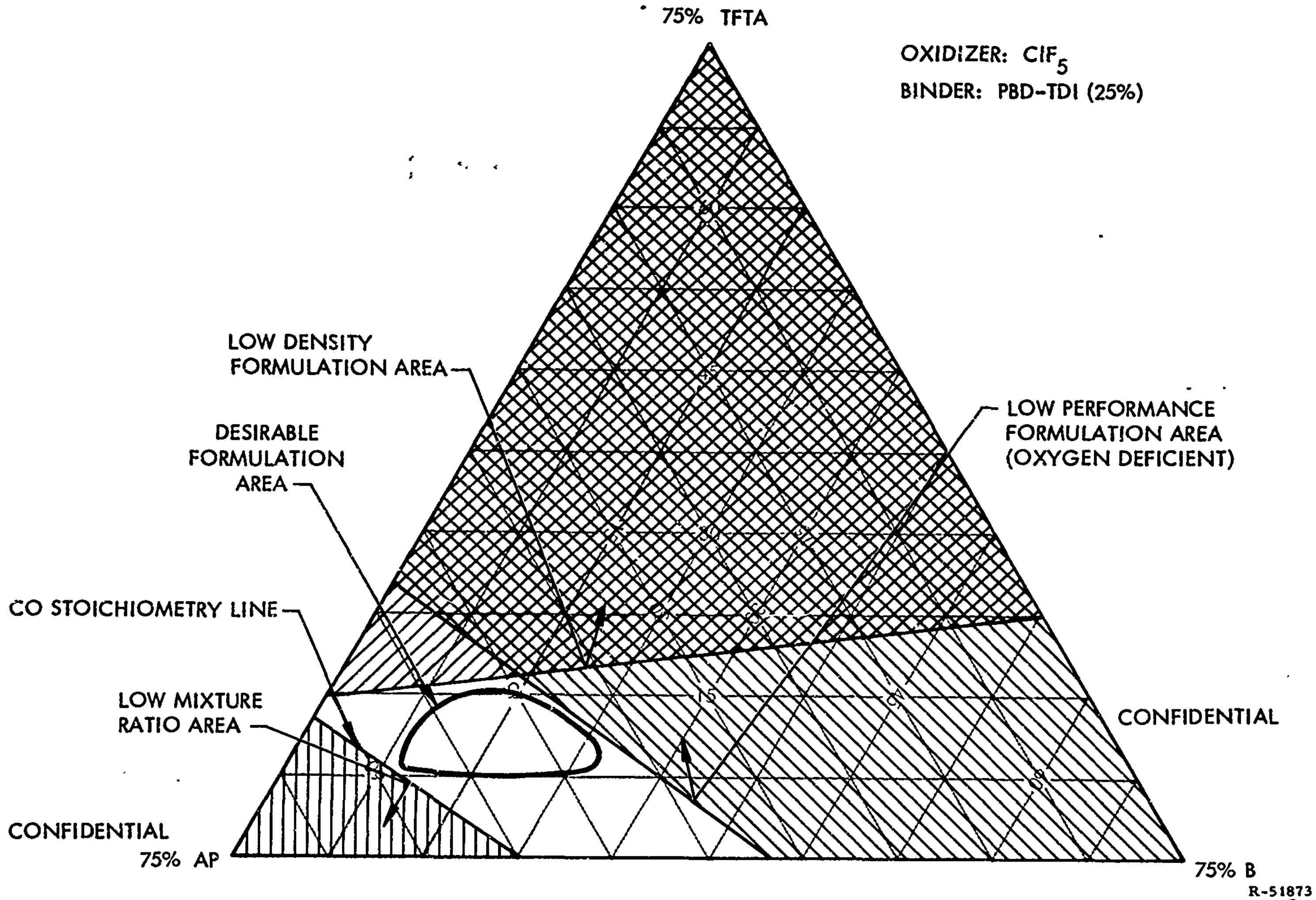

Figure 8. (U) Effect of Composition on the TFTA/B/AP/Binder System

(C) The discussion above does not consider the alternative of adding ClO_3F to the oxidizer to increase the available oxygen. It has generally been found that, at the 175° F temperature limit, adequate oxidizer density is maintained using ClO_3F and specific impulse increased by using a ClF_5/ClO_3F binary system, provided that the ClO_3F level is limited to 10% to 20% of the liquid phase. By adding ClO_3F, the AP requirement is reduced and, therefore, has the effect of shifting the desirable formulation area to lower AP levels. The extent of this shift can be determined from the ClO_3F — AP oxygen equivalence curves presented in figure 9. The rapid decrease in ClO_3F density as its critical temperature is approached precludes its use at the 195° F limit. Figure 10 illustrates the decrease in oxidizer density as a result of increased ClO_3F concentration, indicating the equivalent density of ClF_5/ClO_3F (90/10) at 175° F to ClF_5 (100 at 195° F). It should be noted that adequate propellant bulk density can be maintained while using ClO_3F at the higher (195° F) temperature condition with a ClF_5/BrF_5 ClO_3F ternary oxidizer system; however, the required BrF_5 and ClO_3F would result in a mixture with essentially the same bulk density and performance as obtained by using only ClF_5.

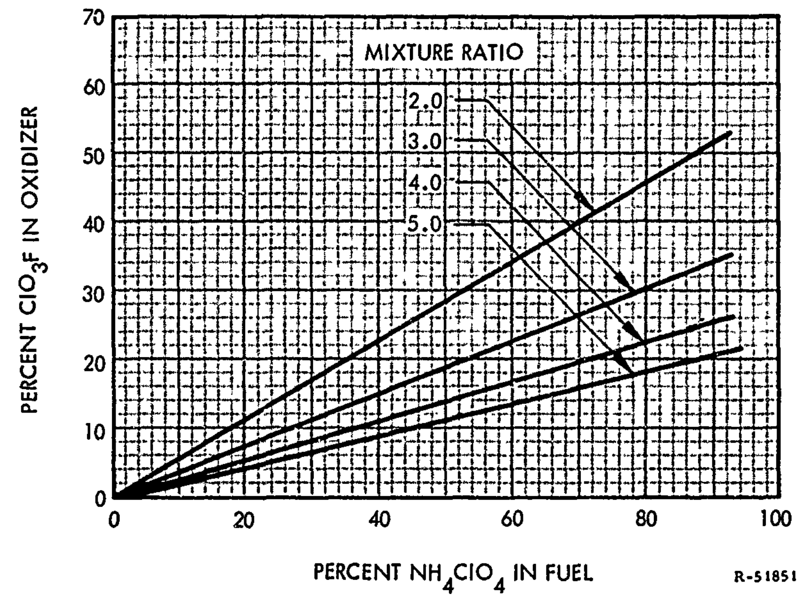

Figure 9. (U) Oxygen Equivalence of ClO_3F and NH_4ClO_4

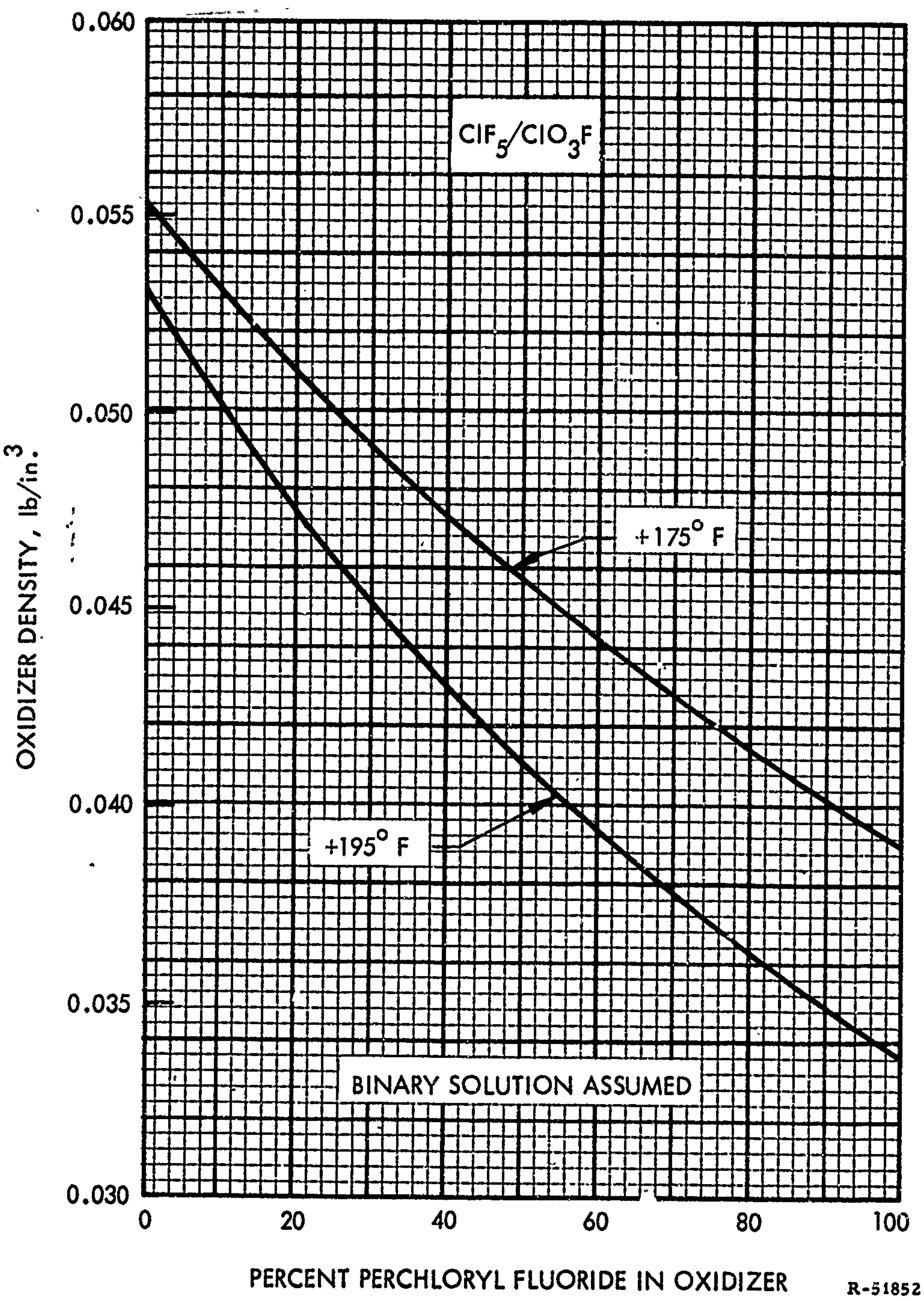

Figure 10. (U) Oxidizer Density as a Function of Composition

SECTION IV

FUEL DEVELOPMENT

(C) Propellant studies have resulted in the successful development of four high density, high specific impulse fuels which are suitable for prepackaged hybrid propulsion systems. However, one and possibly two are not suited for advanced tactical missile applications requiring on-off operation because of their tendency to sustain combustion on termination of oxidizer flow. The fuels all contain TFTA, boron, ammonium perchlorate, and R-binder and all are castable. One of the fuel systems was selected for development of full-scale motors. The selected fuel contains 30% TFTA, 5% boron, 30% AP, and 35% binder, has a theoretical specific impulse of 284 sec and a density impulse of 453 gm-sec/cc when oxidized with ClF_5. With further fuel development, the four component blend has a potential specific impulse of 295 sec and density impulse of 503 gm-sec/cc.

(C) A hybrid fuel grain shape has been developed using the fuel mentioned above which provides a cross sectional loading of 92% with only 6.7% sliver. The grain is 18-in. in diameter and 20-in. long. It uses six "active" fuel ports with seven "inactive" ports clustered about each "active" port to produce essentially constant fuel flow rate as a function of burning time.

(U) The fuel and grain shape have performed as expected in subscale motor tests with durations up to 17 sec and in two full-scale motor tests with durations up to 15 sec.

1. FUEL STUDIES

(U) Four hybrid fuel systems listed in table III have been developed which appear to be applicable to advanced tactical missile propulsion systems.

(C) Each of the fuels is suitable for use with ClF_5 oxidizer and will deliver an increase in performance if ClO_3F is added to the oxidizer in small percentages. Fuel No. 1, which was selected for full-scale motor development, is castable with "as received" ingredients. A 5.0-in. grain of fuel No. 1 above is shown after test in figure 11. Fuel No. 2 requires the boron to be combined in a 1:1 ratio with TFTA in particles called prills, measuring 1/16 in. to 3/16 in. A sample of fuel No. 2 is shown in figure 12. Both fuels have been demonstrated to be nonsustaining in subscale motor tests. Fuel No. 3 uses the AP in pellet form, as shown in figure 13, and

TABLE III

(U) PREPACKAGED HYBRID PROPELLANTS DEVELOPED AND TESTED UNDER THIS CONTRACT

	Fuel System			
	1	2	3	4
TFTA, %	30	22.5	20	15
Boron, %	5	15	9	15
AP, %	30	35	52	40
R-Binder, %	35	27.5	19	30
ClF_5* Oxidizer				
I_{sp}	284	288	294	292
ρI_{sp}	453	475	503	491
ClF_5/ClO_3F Oxidizer Blends				
I_{sp}	289	292	---	---
ρI_{sp}	448	479	---	---
Oxidizer	80% ClF_5/ 20% ClO_3F	90% ClF_5/ 10% ClO_3F	---	---

* Performance figures are approximately 10% lower with ClF_3

has been demonstrated to be nonsustaining in certain subscale tests. However, additional fuel studies are required to be assured of nonsustaining combustion characteristics. Fuel No. 4 is castable with "as received" ingredients but is known to be a sustaining fuel system and is therefore not suited for on-off operation. However, its performance and high regression rate (0.16 in./sec) make it extremely attractive for an application where variable thrust operation is required and restart capability is not.

(U) These fuels were developed in studies which included investigation of propellant system performance, processing techniques, and combustion characteristics. Each fuel represents the maximum performance obtainable with the four components when present state-of-the-art processing techniques and the resultant fuel combustion characteristics are considered.

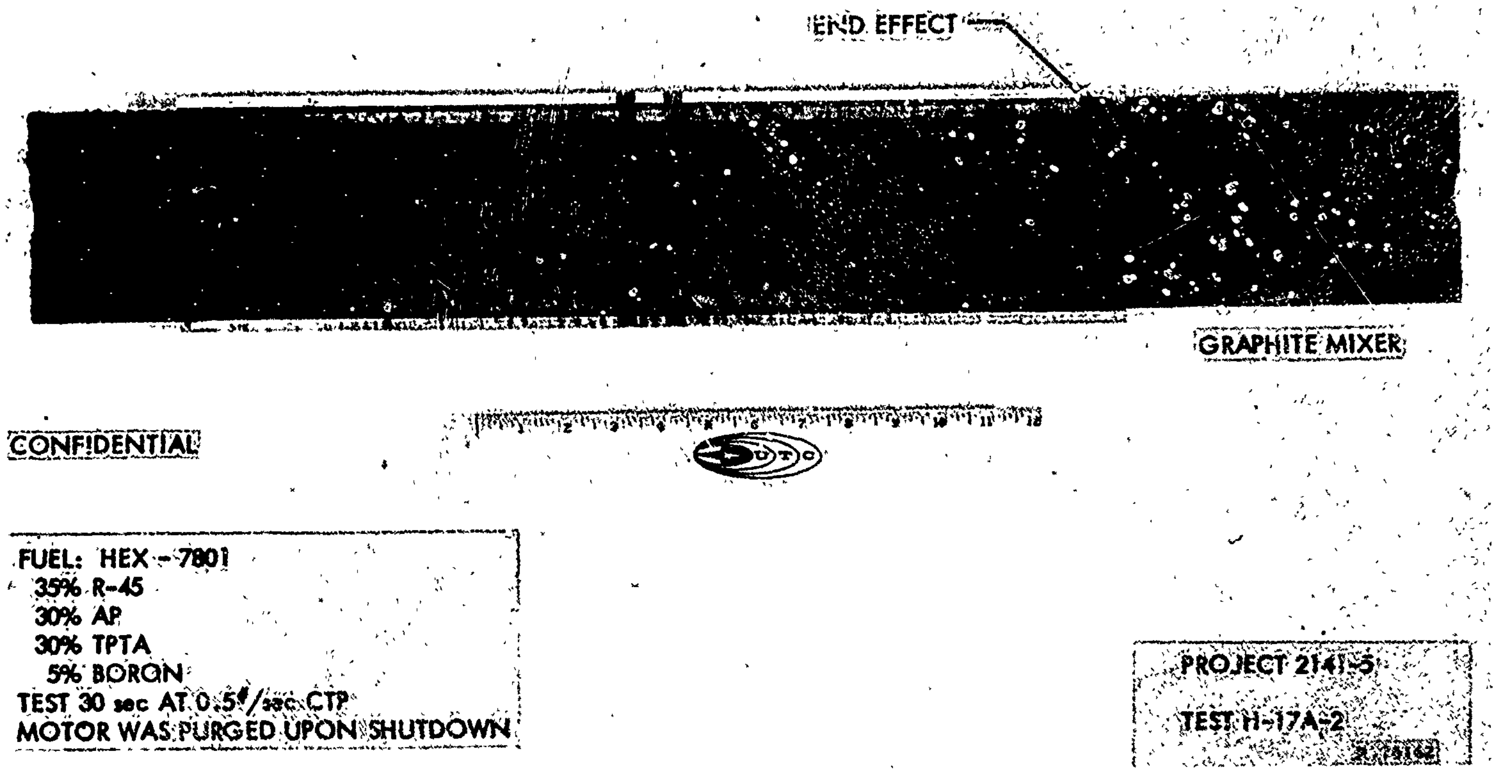

Figure 11. (U) Hybrid Fuel Grain Containing 30% TFTA, 5% Boron, 30% AP, and 35% R-Binder

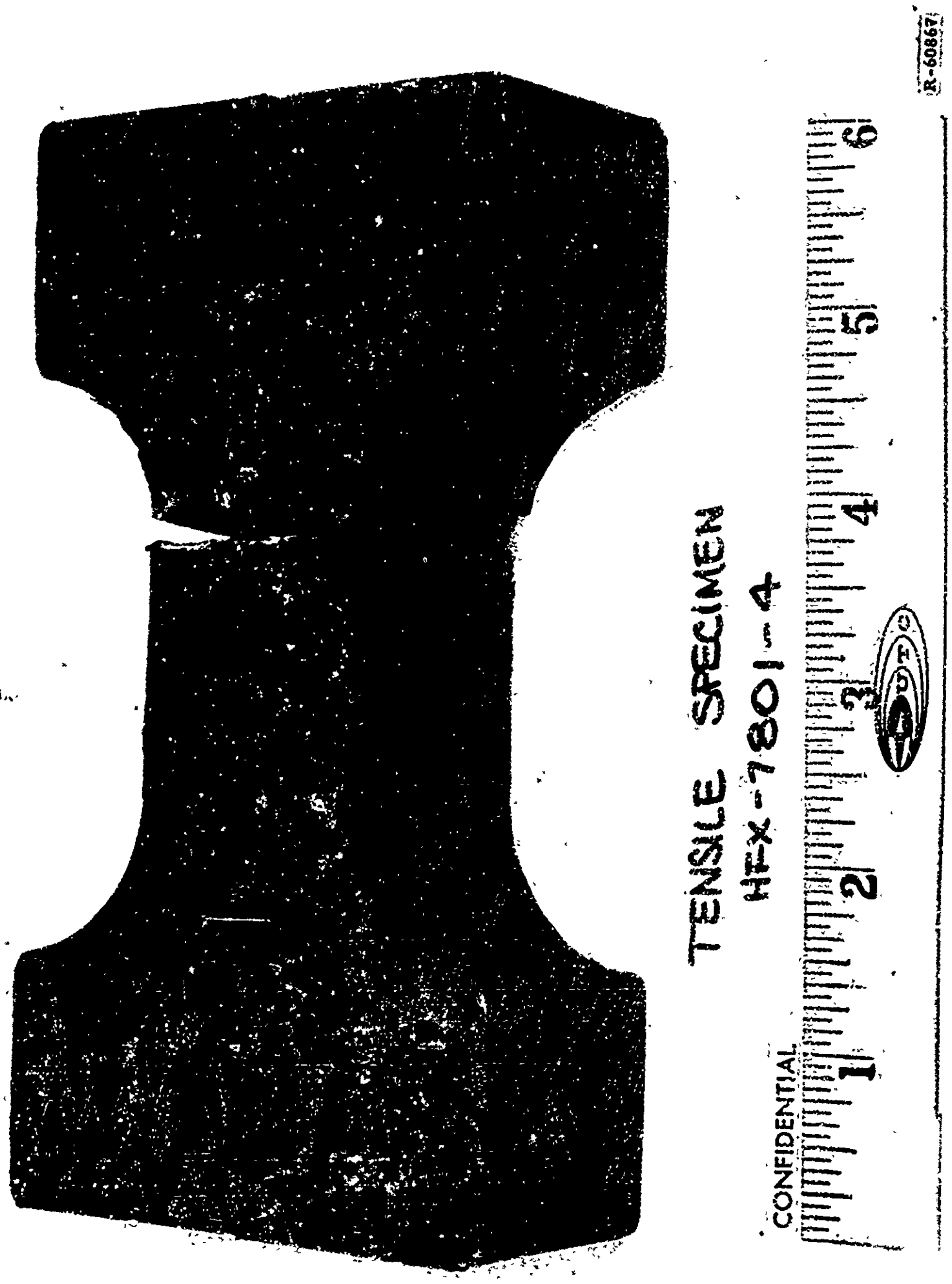

Figure 12. (U) Hybrid Fuel Sample Containing 22.5% TFTA, 15% Boron, 35% AP, and 27.5% R-Binder

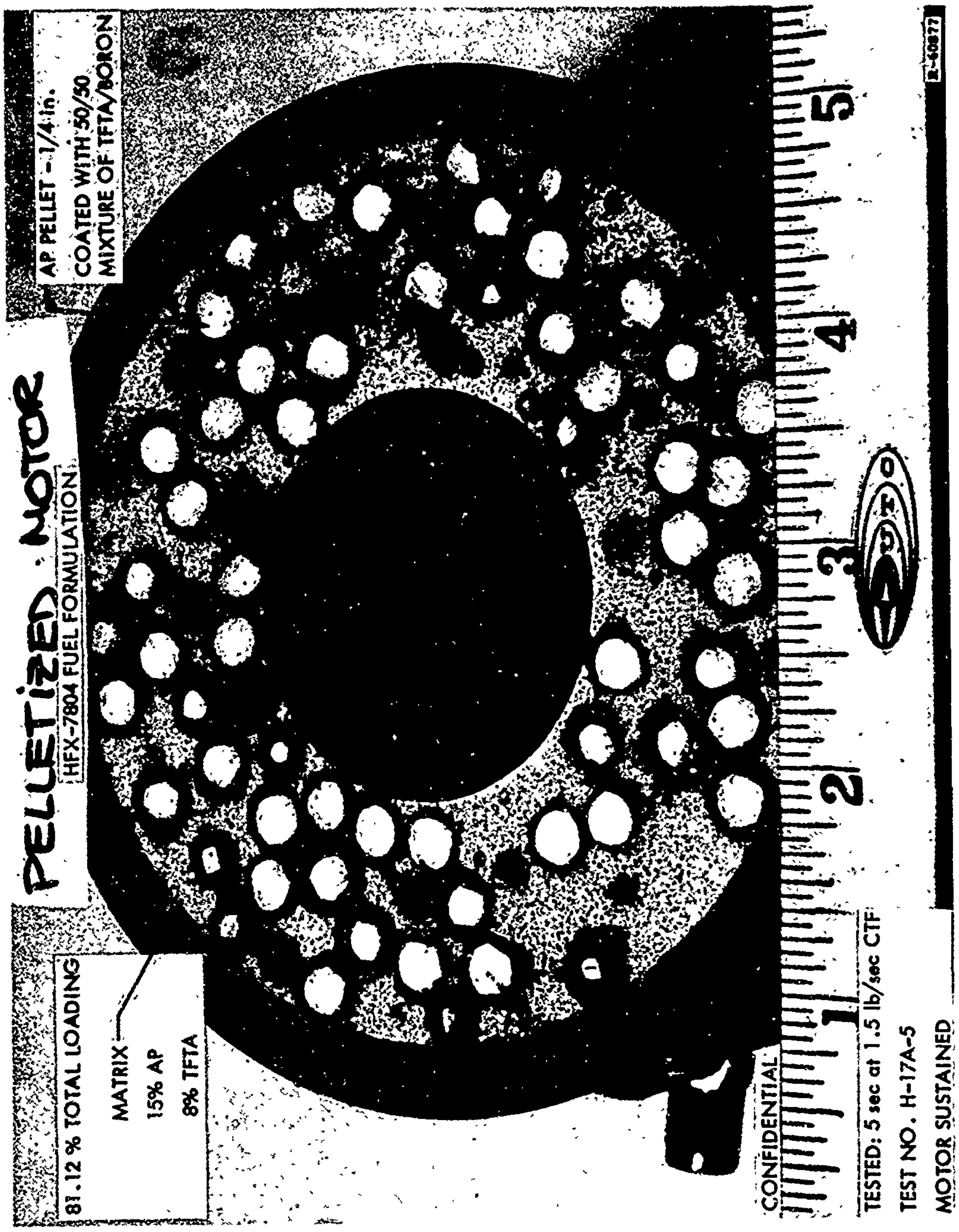

Figure 13. (U) Hybrid Fuel Grain Containing 20% TFTA, 9% Boron, 52% AP, and 19% R-Binder

(U) The fuel development studies were initiated using fuels containing TAZ, boron, AP, and binder designated as QX 3812/DER 332. The TFTA, aluminum, and a hydrocarbon designed as R-binder were retained as alternate fuel ingredients in the event that development problems resulted.

(C) Based on early formulation studies and subscale motor tests, several variations in the selected fuel components were chosen for possible use with ClF_5 and ClO_3F to develop high density, high specific impulse propellants. Each variation, some using alternate fuel components, was selected on the basis of minimizing certain formulation or combustion phenomena which could produce development problems. A number of fuel formulations incorporating the alternate ingredients, listed in table IV, were selected for investigation. Their order is one of decreasing performance and increasing anticipated ease of formulation without resulting in combustion problems. Almost immediately, TFTA was substituted for TAZ which became temporarily unavailable.

(C) During the subscale motor test program, which was conducted to develop one or more of the listed propellant combinations, it was found that nearly all of the formulations tended to sustain combustion after termination of oxidizer flow. It was also found that a crusty char developed in the fuels containing boron which did not occur when aluminum was substituted for boron. Since laboratory differential thermal analysis (DTA) studies had shown that exothermic decomposition of TFTA and QX/DER binder occured at 266° F (130° C), it was then postulated that this decomposition could be contributing to the sustained combustion characteristics. A review of previous testing with R-binder and similar fuel components, which did not sustain combustion, tended to indicate that the R-binder could suppress the tendency to sustain. It was, therefore, decided to discontinue further investigation of fuels containing the QX/DER binder and continue work with R-binder systems.

(C) The fuels development effort has produced two noteworthy achievements:

A. Solids loading levels of up to 85% have been obtained by special compacting techniques. Approximately 60% solids loading can be achieved with "as received" TFTA, boron, and AP. This loading can be further increased up to about 65% or 70% using compacting techniques and up to nearly 75% using coarse particle AP. An ultimate loading of 80% to 85% is feasible with pelletized components.

B. Nonsustaining fuels were tested which contained up to 40% AP. Previously, 15% AP was considered to be the upper limit of solids loading without producing sustaining combustion. The higher loading level was achieved by substituting 800μ size AP for the nominal 175μ "as received" AP.

TABLE IV

(U) HYBRID PROPELLANT COMBINATIONS
INITIALLY SELECTED FOR EVALUATION

Type of Fuel	Composition	Oxidizer	I_{sp}	ρI_{sp}	O/F
Pelletized	33% TAZ/20% B/27% AP/20% Binder	ClF_5	294	495	2.3
Pelletized	22% TFTA/20% B/38% AP/20% Binder	ClF_5	293	494	2.3
Homogeneous	35% TAZ/20% B/15% AP/30% Binder	90% ClF_5/ 10% ClO_3F	293	479	2.5/ 2.9
Pelletized	60% TFTA/20% B/20% Binder	75% ClF_5/ 25% ClO_3F	297	468	3.5
Homogeneous	45% TFTA/20% B/35% Binder	75% ClF_5/ 25% ClO_3F	295	461	3.5
Pelletized	22% TFTA/20% Al/38% AP/20% Binder	ClF_5	289	486	1.5
Homogeneous	35% TFTA/20% Al/15% AP/30% Binder	80% ClF_5/ 20% ClO_3F	288	455	2.2

(C) Combustion has also been demonstrated with AP loading as high as 52% with the AP in the form of 3/16-in. -diameter pellets. However, the metal additive in this case was aluminum rather than boron.

(U) Several fuel systems using the R-binder were selected for continued development. The effort led ultimately to the successful development of the fuels previously described. Two of the fuels qualified for full-scale motor development for which initiation was already delayed as a result of the fuel development problem. However, fuel No. 1 was selected for full-scale motor development because it would provide fewer processing difficulties in scaling up from laboratory batch sizes (80 lb) to full-scale motor batches (250 lb), and had been found to have nonsustaining combustion characteristics under more adverse conditions.

a. Propellant Performance

(C) The maximum performance of a four-component fuel containing TFTA, boron, AP, and R-binder with ClF_5 oxidizer occurs when the fuel binder level is held to 20%. Maximum specific impulse and density impulses are 294.7 sec, 503.1 gm-sec/cc and 290.9 sec, 507.7 gm-sec/cc are obtainable, emphasizing first maximum specific impulse then maximum density impulse.

(C) However, processing limitations do not at present permit the formulation of castable homogeneous fuel blends with only 20% binder. In addition, high AP loading levels and high boron loading levels contribute to sustaining combustion. Compromises were, therefore, made in the formulation. In order to obtain the maximum performance while imposing actual limitations on the formulation, calculations were conducted over varying percentages of the critical ingredients.

(C) The results of the calculations are shown in table V. These results are presented in table V (A) as a function of varying boron content with the binder content held constant, and maintaining AP levels sufficient to oxidize all carbon. In table V (B), the binder level and AP content are constant while the boron and TFTA are varied. In table V (C) the AP level is held constant. The potential benefit which could be gained by using the QX/DER binder is evident by comparing the figures of table V (D) with those of table V (A). Approximate trends can be established by cross-referencing.

TABLE V

(U) SUMMARY OF PERFORMANCE CALCULATIONS
TFTA-BORON-AP-BINDER FUEL SYSTEM

TFTA %	Boron %	AP %	Binder %	O/F	I_{sp}	ρI_{sp}
A. R-Binder, Binder Constant						
19	5	56	20	1.5	292.1	487.5
16	10	54	20	1.5	292.9	493.0
13	15	52	20	2.0	294.4	503.1
10	20	50	20	2.5	293.1	506.8
8	25	47	20	2.5	292.2	507.6
5	30	45	20	2.5	290.7	507.9
0	40	40	20	3.0	287.1	507.9
B. R-Binder, Binder and AP Constant						
30	5	40	25	1.5	287.6	463.9
25	10	40	25	2.0	288.8	477.7
20	15	40	25	2.0	288.7	481.8
15	20	40	25	2.5	288.2	483.3
10	25	40	25	3.0	287.7	489.7
C. R-Binder, AP Constant						
20	25	30	25	2.5	285.6	482.9
25	20	30	25	2.5	286.4	480.3
30	15	30	25	2.0	287.4	473.1
30	10	30	30	2.0	287.1	465.1
30	5	30	35	2.0	283.9	453.1
D. QX-Binder, Binder Constant						
27	10	43	20	2.0	292.3	
25	15	40	20	2.0	293.3	
22	20	38	20	2.5	292.9	
19	25	36	20	2.5	291.9	
16	30	34	20	3.0	290.7	507.0
20	15	45	20	2.0	293.1	
25	20	35	20	2.5	291.2	

b. Propellant Ingredients

(C) The initially conceived fuel system contained TAZ, boron, AP, and binder. The selected fuel system contains TFTA, boron, AP and binder. Some of the considerations involved in selection of the fuel ingredients are discussed in this section.

1. Binder

(U) The binder used during the initial investigation of high density impulse propellants was a hydrocarbon binder designated as R-binder. This binder has already been extensively tested on Contract AF 04(611)-8516 and UTC-sponsored programs and had been demonstrated to be nonsustaining in nearly all formulations. Just prior to initiation of this contract, the QX/DER binder was selected for development because of its greater oxygen content and its potential for increasing performance or reducing the AP content.

(C) As interhalogen oxidizers, in general, are poor oxidizers for carbon-containing fuels, it is desirable for good performance to minimize the carbon content and increase the oxygen content of the binder. In order to include an oxidizing element for carbon, thereby improving performance, various oxygen-containing binders were investigated. This investigation resulted in the selection of the QX/DER binder. This binder, more accurately designated QX 3812/DER 332, was studied extensively during this program. It contains 61.5% carbon and 20% oxygen as compared to 80% carbon and 10% oxygen in the R-binder. In a typical fuel system oxidized by ClF_5 and ClO_3F, the ClO_3F content can be reduced by 5% using the QX/DER binder, and similar reductions are possible in AP loading. Table VI describes the typical performance levels which are theoretically attainable using the QX/DER binder. Each system is optimized at its best performance blend, so differences in formulation ratios exist.

(C) As an added advantage, the QX/DER binder offers slightly higher density (1.1 gm/cc as compared to 1.0 gm/cc for the R-binder system), and formulation studies conducted with the QX/DER binder indicate that up to a 10% increase in solids loading over that with the R-binder is possible because of its lower viscosity. Typically, boron solids loading can be increased from approximately 47% to 53%.

TABLE VI

(U) PERFORMANCE OF QX/DER VERSUS R-BINDER SYSTEM

Fuel	Oxidizer	I_{sp} sec	ρI_{sp} gm-sec/cc³	O/F
60% TFTA/20% Boron/ 20% R-Binder	70% ClF_5/30% ClO_3F	294	461	4.0
60% TFTA/20% Boron/ 20% QX Binder	75% ClF_5/25% ClO_3F	296	467	3.5
30% TAZ/25% Boron/ 25% AP/20% R-Binder	ClF_5	289	499	2.75
30% TAZ/25% Boron/ 25% AP/20% QX Binder	ClF_5	293	505	2.50

(C) Because of the improvements in performance and solids loading made possible by the use of the QX/DER binder, it appears to be a superior system for application in high density hybrid fuel systems and, therefore, deserves continued investigation. However, since the beginning of this contract, conflicting data have been obtained concerning sustaining character of fuels containing the QX/DER binder. These include 5.0-in.-diameter motor data obtained under Contract AF 04(611)-8516 and 3.5-in. tests conducted on this contract. Under the other contract, fuels containing TFTA, aluminum, AP, and QX/DER binder did not sustain combustion when tested with ClF_3. The same components tested in three 12-in.-diameter motors did not sustain combustion in one test but did on two subsequent tests. Similar tests conducted with boron and the QX/DER binder consistently produced sustained combustion. Such contradictory data are possible with marginally nonsustaining fuels as a result of motor parts which tend to store heat energy and impose additional heat loads on the fuel after shutdown by thermal radiation. The tests discussed later, which were conducted to resolve the discrepancy, resulted in sustained combustion with fuels using QX/DER binder and AP loading levels as low as 5%.

(C) The data suggests that the sustaining reaction is one that consumes the binder, TFTA, and AP and is augmented by any char buildup that results from the use of boron. The existence of this char and its relation to the boron was borne out in a series of tests conducted with boron and aluminum additives which are described later.

(U) The decision to discontinue use of the QX/DER binder system was finally based on laboratory differential thermal analysis (DTA), which revealed that TFTA decomposes endothermically at about 110° C and that the products evolved react exothermically with the QX/DER binder at 130° F. Similar exotherms do not result with the R-binder and TFTA.

(U) The existence of an exothermic reaction in itself is not cause for discontinuing use of the QX/DER binder, since exothermic reaction of other fuel components is exploited to obtain higher regression rates. However, when the binder system contributes to the reaction, the separation of particles involved in the reaction is not possible and sustained combustion tends to result. Further study might reveal a means by which the QX/DER binder can be used, but for now the R-binder holds greater promise in the development of a high density hybrid fuel system.

(C) Laboratory DTA studies similar to those conducted with the QX/DER system have been conducted with the R-binder and the various ingredients. The results of these studies indicate that exotherms similar to those obtained with the QX/DER binder do not exist. The DTA studies were conducted with R-binder; binder and boron; binder, boron and AP; binder, TFTA, AP; and binder, TFTA, boron and AP. None of the tests exhibited exotherms below 225° C.

(C) The reversion at this point to the use of the R-binder system was not made without supporting experience. Tests conducted with the R-binder under both this and other programs are summarized in table VII. These tests include extensive use of TAZ, TFTA, triaminoguanidine-azide/hydrazine azide (THA), boron, and AP additives to increase regression rate and improve performance.

TABLE VII

(U) SUMMARY OF TEST EXPERIENCE WITH R-BINDER CONTAINING NITROGEN ADDITIVES, BORON, AND AMMONIUM PERCHLORATE

Test Number	Binder, %	Fuel Components AP, %	Metal, %	N, %	Oxidizer	P_c psia	$\dot{w}_{ox}$ lb/sec	t_b sec	$\bar{r}$ in./sec	Comments*
R-Polymer (3.5-in. Motors)										
L40236	100 R/TDI				CTF	463	0.225	12.6	0.012	
H15A14	100 R/TDI				CTF	560		11.9	0.015	
R-Polymer + Boron (3.5-in. Motors)										
L40230	50 R/TDI		50		CTF	490	0.290	9.7	0.019	
R-Polymer + AP (3.5-in. Motors)										
H15A13	92.5 R/TDI	7.5			CTF	583		12.0	0.014	
H15A12	90 R/TDI	10			CTF	575		12.5	0.018	
H15A4	87.5 R/TDI	12.5			CTF	638		9.7	0.023	
H15A3	85 R/TDI	15			CTF	697		1.4		
H15A2	82.5 R/TDI	17.5			CTF	643		11.5	0.023	
H15A1	80 R/TDI	20			CTF	927		4.6	0.021	
R-Polymer + Boron + AP (3.5-in. Motors)										
L40231	50 R/TDI	25	25		CTF	454	0.297	19.2	0.038	Sustained
L40232	40 R/TDI	30	30		CTF	542	0.298	19.4	0.036	Sustained
R-Polymer + TAZ (3.5-in. Motors)										
L40238	65 R/TDI			35 TAZ	CTF	729	0.302	12.8	0.022	
R-Polymer + TAZ + AP (3.5-in. Motors)										
L40240	57.5 R/TDI	7.5		35 TAZ	CTF	724	0.300	12.7	0.027	
L40242	55 R/TDI	10		35 TAZ	CTF	741	0.302	1.5	0.038	
L40246	52.5 R/TDI	12.5		35 TAZ	CTF	774	0.300	4.7		
L40247	50 R/TDI	15		35 TAZ	CTF	700	0.300	12.3	0.035	
R-Polymer + TAZ + AP + B (3.5-in. Motors)										
L40234	42 R/TDI	4	25	29 TAZ	CTF	490	0.295	19.6	0.034	
L40224	42 R/TDI	4	25	29 TAZ	CTF	595	0.741	5.4		
L40227	42 R/TDI	4	25	29 TAZ	CTF	610	0.741	9.8	0.046	
L40225	42 R/TDI	4	25	29 TAZ	CTF	527	0.761	5.2	0.051	
L40226	42 R/TDI	4	25	29 TAZ		925		1.0		

* All tests not noted otherwise were nonpelletized, nonsustaining, and noncharring

TABLE VII

(U) SUMMARY OF TEST EXPERIENCE WITH R-BINDER CONTAINING NITROGEN ADDITIVES, BORON, AND AMMONIUM PERCHLORATE (Continued)

Test Number	Binder, %	Fuel Components AP, %	Fuel Components Metal, %	N, %	Oxidizer	P_c psia	$\dot{w}_{ox}$ lb/sec	t_b sec	$\bar{r}$ in./sec	Comments*
R-Polymer + TFTA + B (3.5-in. Motors)										
L40229	55 R/TDI		27	18 TFTA	CTF	1175	0.295	0.9		
R-Polymer + TFTA + B (3.5-in. Motors)										
L40244	55 R/TDI	10		35 TFTA	CTF	486	0.300	12.8	0.020	
L40243	55 R/TDI	10		35 TFTA	CTF	626	0.300	1.1		
R-Polymer + TFTA + AP + B (3.5-in. Motors)										
L40233	19 R/TDI	21	31	29 TFTA	CTF	243	0.296	14.8	0.056	Pelletized
L40235	39 R/TDI	4	26	31 TFTA	CTF	683	0.293	14.5	0.045	
R-Polymer (5-in. Motor)										
L40342-3	100				CTF	685	1.142	10.0	0.035	
R-Polymer + AP + Boron (5-in. Motor)										
L40344	70	10	20 B		CTF	765	1.146	10.0	0.036	
R-Polymer + TFTA (5-in. Motor)										
L40345	55			45 TFTA	CTF	695	1.135	10.0	0.038	
R-Polymer + THA (5-in. Motors)										
L60211	50			50 THA	FLOX	99	0.26	28.6	0.0379	
L60212	50			50 THA	FLOX	46	0.26	40.6		
L60213	50			50 THA	FLOX	446	0.26	18.5	0.0327	
L60214	50			50 THA	FLOX	710	0.25	8.4	0.0813	
L60216	50			50 THA	FLOX	100	1.10	20.3	0.0479	
L60217	50			50 THA	FLOX	133	1.09	18.4	0.0483	
L60218	50			50 THA	FLOX	234	1.10	14.3	0.0576	
L60219	50			50 THA	FLOX	378	1.10	11.4	0.0856	
L60220	50			50 THA	FLOX	116	1.67	14.6	0.070	
L60221	50			50 THA	FLOX	192	1.67	11.1	0.082	
L60222	50			50 THA	FLOX	272	1.67	9.1	0.070	
L60223	50			50 THA	FLOX	397	1.69	8.3	0.077	
L60224	50			50 THA	FLOX	58	0.74	18.5	0.043	

* All tests not noted otherwise were nonpelletized, nonsustaining, and noncharring

TABLE VII

(U) SUMMARY OF TEST EXPERIENCE WITH R-BINDER CONTAINING NITROGEN ADDITIVES, BORON, AND AMMONIUM PERCHLORATE (Continued)

Test Number	Binder, %	Fuel Components AP, %	Fuel Components Metal, %	N, %	Oxidizer	P_c psia	$\dot{w}_{ox}$ lb/sec	t_b sec	$\bar{r}$ in./sec	Comments*
L60225	50			50 THA	FLOX	120	0.74	17.5	0.044	
L60226	50			50 THA	FLOX	278	0.74	16.4	0.049	
L60227	50			50 THA	FLOX	361	0.74	15.5	0.056	
R-Polymer + THA (5-in. Motors)										
L60229	50			50 THA	FLOX	60	0.74	20.3	0.039	
L60230	50			50 THA	FLOX	134	0.74	19.2	0.045	
L60231	50			50 THA	FLOX	474	0.74	18.4	0.050	
L60232	50			50 THA	FLOX	516	0.75	17.5	0.051	
L60233	50			50 THA	FLOX	79	0.26	24.75	0.030	
L60234	50			50 THA	FLOX	369	0.75	17.66	0.048	
L60239	50			50 THA	FLOX	500	1.13	15.01	0.066	
L60240	50			50 THA	FLOX	586	1.65	13.02	0.071	
L60291	50			50 THA	FLOX	382	0.282	2.12	0.156	
L60292	50			50 THA	FLOX	404	0.283	4.08	0.102	
L60293	50			50 THA	FLOX	407	0.281	8.24	0.874	
L60294	50			50 THA	FLOX	442	0.283	16.22	0.065	
L60279	50			50 THA	LOX	30	0.58	19.81	0.017	
L60280	50			50 THA	LOX	71	0.59	18.80	0.024	
L60281	50			50 THA	LOX	270	0.59	17.88	0.038	
L6020	50			50 THA	LOX	337	0.56	16.11	0.037	
R-Polymer + THA (2-in. Motors)										
H7A-109	50			50 THA	FNA		0.56			
H7A-110	50			50 THA	FNA		0.56			
H7A-111	50			50 THA	IRFNA	665/170	0.56	3.8	0.11	
H7A-112	50			50 THA	MDNA	500/600	0.56	5.0	0.10	
H7A-113	50			50 THA	MDNA	725/465	0.55	4.82	0.11	
H7A-114	50			50 THA	MDNA	965/515	0.55	4.94	0.10	
H7A-115	50			50 THA	MDNA	1015/830	0.80	2.70	0.198	
H7A-116	50			50 THA	MDNA	1060/965	0.58	3.37	0.152	
H7A-117	50			50 THA	MDNA	1040/965	0.57	2.3	0.173	
H7A-118	50			50 THA	IRFNA		0.6			

* All tests not noted otherwise were nonpelletized, nonsustaining, and noncharring

TABLE VII

(U) SUMMARY OF TEST EXPERIENCE WITH R-BINDER CONTAINING NITROGEN ADDITIVES, BORON, AND AMMONIUM PERCHLORATE (Continued)

Test Number	Binder, %	Fuel Components AP, %	Metal, %	N, %	Oxidizer	P_c psia	$\dot{w}_{ox}$ lb/sec	t_b sec	$\bar{r}$ in./sec	Comments*
H7A-119	50			50 THA	IRFNA		0.6			
H7A-120	50			50 THA	IRFNA		0.6	11.6		
H7A-121	50			50 THA	IRFNA		0.6			
H7A-122	50			50 THA	IRFNA		0.6			
H7A-123	50			50 THA	IRFNA		0.6			
H7A-124	50			50 THA	IRFNA	300/700	0.6	2.17	0.12	
H7A-125	50			50 THA	IRFNA	1065	0.6	2.09	0.18	
H7A-126	50			50 THA	IRFNA	730	0.60	1.99	0.16	
H7A-127	50			50 THA	IRFNA	1007	0.60	1.69	0.16	
H7A-128	50			50 THA	IRFNA	953	0.60	2.65	0.16	
H7A-129	50			50 THA	IRFNA		0.60			
H7A-130	50			50 THA	IRFNA		0.60			
R-Polymer + THA (2-in. Motors)										
H7A-131	50			50 THA	IRFNA	950	0.60	1.52	0.16	
H7A-132	50			50 THA	IRFNA	835	0.60	2.61	0.16	
H7A-133	50			50 THA	IRFNA	864	0.60	2.51	0.16	
H7A-134	50			50 THA	IRFNA	920	0.60	2.06	0.16	
R-Polymer + THA + Al + TDI (5-in. Motors)										
H6A-36	30		20 Al	50 THA	RFNA	556	0.94	4.85	0.130	
H6A-37	30		20 Al	50 THA	RFNA	272	0.94	4.90	0.104	
H6A-38	30		20 Al	50 THA	RFNA	730	0.92	4.10	0.134	
A0687	30		20 Al	50 THA	LOX	72.8	0.40	15.18	0.031	
A0688	30		20 Al	50 THA	LOX	108.4	0.61	8.4	0.035	
A0690	30		20 Al	50 THA	LOX	209	1.23	5.92	0.076	
R-Polymer + THA (5-in. Motors)										
A0716		50		50 THA	FLOX	145	0.465	13.2	0.042	
A1717		50		50 THA	FLOX	390	1.36	4.2	0.195	
A0718		50		50 THA	FLOX	68	0.167	35.57	0.012	
A0719		50		50 THA	FLOX	513	1.75	3.24	0.013	
A0720		50		50 THA	FLOX	197	0.75	8.52	0.050	

* All tests not noted otherwise were nonpelletized, nonsustaining and noncharring

2. Boron

(C) Boron is the primary additive of the multiple component fuel, because of its high density and relatively high performance with interhalogen oxidizers. There exist two areas of investigation which are important to the successful formulation of boron-containing fuels. The first is the loading level of boron achievable in multiple-component fuels, and the second is the combustion behavior. Boron "as received" can be loaded to approximately 47% of a total blend with R-binder and to a lesser extent when other components are included. Generally, the level of TFTA and boron combined cannot exceed the binder content. Boron loading levels of 20% to 30% are practical, but the boron must be compacted, prilled, or added to AP pellets to achieve extremely high loadings. Higher loading levels using "as received" materials result in fuel mixes which are too viscous to be castable. Satisfactory combustion of boron has been found to be related to both the fuel regression rate and the boron loading level, i.e., the level of boron in homogeneous fuel blends or the level of boron in the matrix of compacted or large-particle-containing fuels. Lower percentages of boron (less than 20%) usually burn satisfactorily, whereas, loading levels greater than 20% burn satisfactorily only if high regression rates are obtained. Without regression rate augmentation, there appears to be a tendency for the boron to sinter or char rather than burn where the concentration exceeds 20%. Boron also tends to aggravate existing sustaining problems because of its tendency to form a char layer by absorbing heat and transferring it to the fuel grain after motor shutdown.

3. Nitrogen Additives (TFTA, TAZ, THA)

(C) Three nitrogen-containing additives have been included in hybrid fuel research investigations conducted in the past. Triaminoguanidine-azide (TAZ); its double salt, THA; and TFTA have been studied in the past as a means of augmenting hybrid fuel regression rate. Work with THA was discontinued because of its thermal stability limitations. In addition to increasing regression rate as a result of their high energy release, the crystalline additives increase the ratio of hydrogen and nitrogen to carbon in the fuel, which is desirable to obtain high performance with interhalogen oxidizers.

(C) The use of TAZ results in higher performance multicomponent fuels or results in lower AP loading levels as is indicated by table VIII. However, the performance advantage is reduced because of the unavailability and relatively high cost of TAZ as compared to TFTA. Comparisons of four-component fuels are made with optimized formulations. Since experimental work conducted with TFTA has demonstrated it to be as effective as TAZ, the full-scale motor fuel development included only TFTA. Until a more significant advantage with TAZ can be seen, TFTA is an adequate substitute.

(U) Tetraformaltrisazine (TFTA) has the chemical formula $C_4H_{12}N_6$, and consists of 33.35% carbon, 8.4% hydrogen, and 58.4% nitrogen by weight. Extensive work which has been completed on TFTA is reported in the literature.*

TABLE VIII

(U) COMPARISON OF PERFORMANCE OF TFTA VERSUS TAZ-CONTAINING FUELS

TFTA vs TAZ	Oxidizer	I_{sp} sec	I_{sp} gm-sec/cc³	O/F
50% TFTA/ 50% R-Binder	50% ClF_5/50% ClO_3F	288	---	3.0
50% TAZ/ 50% R-Binder	50% ClF_5/50% ClO_3F	290	---	3.0
19% TFTA/25% B/ 26% AP/ 20% QX Binder	ClF_5	292.7	496.8	3.0
29% TAZ/25% B/ 36% AP/ 20% QX/DER Binder	ClF_5	292.0	496.6	3.0

* Stolle, R., BER 40 1505. 1907. Hoffman, K., and D. Storm, BER 45 1728, 1912. Nevreiter, J., Am. Chem. Soc., 81 2910, 1959. Food Machinery Corporation, Classified Lit, 1960.

(U) Laboratory studies were conducted with UTC-produced TFTA to resolve discrepancies in properties of TFTA reported in the literature. The heats of formation and combustion of unrecrystallized TFTA were determined and compared favorably to that as reported by Food Machinery Corporation (FMC). The compared values are as follows:

	UTC	FMC
H_f	= +83.9±1.5 K-cal/mole	+86.24 K-cal/mole
H_c	= 6.033±0.012 K-cal/gm	-6.0 K-cal/gm.

(U) Impact sensitivity tests yielded no fires at 150 Kg-cm (3 gm wt at 50 cm), indicating that TFTA is essentially insensitive to impact. The density of TFTA as determined at UTC 9 pycnometer) was found to be 1.31 gm/cc and in pressed form in 1.09 gm/cc.

4. Ammonium Perchlorate

(U) Ammonium perchlorate has a dual role in the multiple-component fuel systems. It provides oxygen to react with carbon contained in the fuel system and also augments the regression rate.

(U) Ammonium perchlorate can be loaded in binder matrices up to approximately 85% depending on particle size. In small particle sizes (40μ to 200μ), AP has been found to produce sustained combustion at levels exceeding 15% loading. However, nonsustaining hybrid fuels have been tested with 40% loading using 600μ to 800μ particle AP.

(C) Maximum performance of fuels containing TFTA, boron AP, and R-binder occurs when the AP level is approximately 50%. However, with homogeneous formulations this level will produce sustained combustion. To produce nonsustaining combustion characteristics, a reduced level of AP loading is required. The ClO_3F can be used to recover the performance lost by reducing AP loading as discussed previoulsy, but only at the expense of reducing oxidizer bulk density.

c. Formulation and Processing

(U) The formulation of a multicomponent fuel is controlled by processing limitations imposed by the ingredients individually and by combination with other ingredients. Processing studies were conducted during the program to provide the means by which the four components could be combined in the highest performance nonsustaining formulation. Included in these studies were investigation of solids loading, particle size improvement, thermal stability, and physical properties. The results of these studies are discussed in the following paragraphs.

1. Solids Loading

(C) The maximum achievable loading for castable fuels varies from 60% to 80% depending on the constituents and their relative particle sizes. Boron is available in two forms, amorphous and crystalline. Only amorphous boron is considered for use because of the extremely high cost of crystalline boron. Amorphous boron is available in particle sizes up to 40μ. However, "as received" boron has a distribution of particles sizes from less than 1μ up to 40μ, and it is the small particle material that limits castability. It appears that "as received" elemental boron is limited to a maximum loading of 50% in binder.

(C) In similar fashion TFTA and TAZ are limited to approximately the same limit. Therefore, the combined TFTA and boron loading limit is also 50%. The TFTA is received in a distribution of particles which is between 0μ and 250μ in size with approximately 70% between 0μ and 100μ.

(U) Ammonium perchlorate is available in particle sizes from 175μ to 800μ and does not impose limitations on processing in any size range.

2. Processing

(C) Because of limitations placed on maximum solids loading limits by the "as received" constituents, processing studies were conducted to find the means of increasing the maximum limit. These studies resulted in the development of several techniques which can be used to increase the maximum solids loading up to 85%. These techniques include compacting of the TFTA, agglomeration of TFTA, boron, and AP into larger particles called prills, and pelletization of TFTA, AP, with or without boron.

(C) Compacted TFTA or TFTA and boron, as shown in figure 14, has been used to increase the maximum loading of those two ingredients. The TFTA or TFTA and boron are pressed into slabs which are then broken into chunks and then added to the fuel matrix. Fuel grains up to 12 in. in diameter, as shown in figure 15, have produced using this technique.

(C) Large particles, called prills, can be produced from any of the fuel ingredients to increase solids loading. The particles are made by mixing the ingredients in a slurry with a soluble binder and a volatile solvent. The mix is tumbled and vacuum dried to produce particles of any desirable size. The use of prills made in a 1:1 ratio of boron and TFTA permit an increase in the solids loading from approximately 50% with "as received" ingredients to almost 75%.

Figure 14. (U) Boron/TFTA Chunks

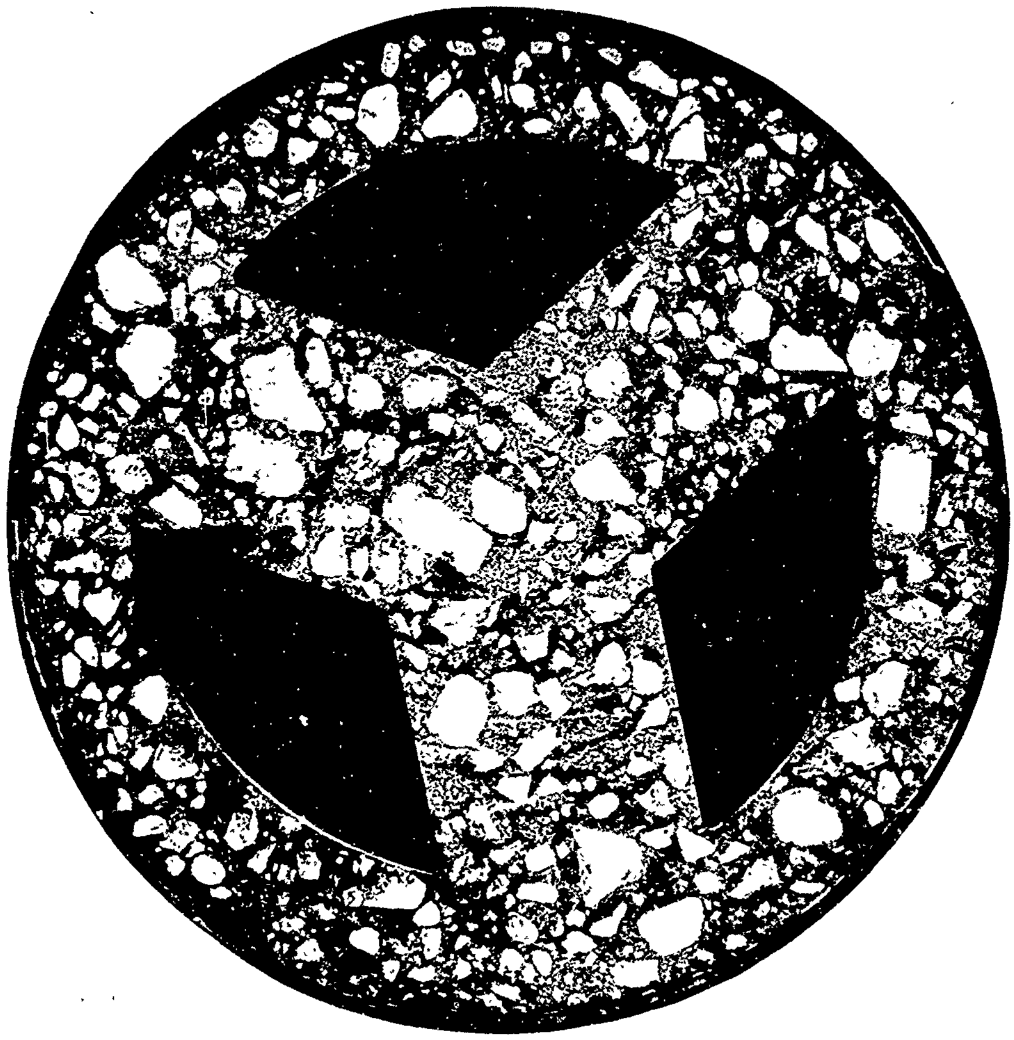

Figure 15. (U) 12-in. Hybrid Fuel Grain

(C) The particles can be made to practically any size. Typical of those used are the AP, boron/AP, boron/TFTA, and AP coated with boron/TFTA particles shown in figures 16, 17, 18 and 19.

(C) Another technique to increasing the solids loading of a fuel system is that of pelletizing the fuel ingredients. By pelletizing, it is possible to attain more than 80% solids loading and yet retain the advantages of castable fuels. Pelletizing is accomplished by machine pressing the fuel ingredients in 3/16-in. or 1/4-in. spherical pellets similar to those shown in figures 20 and 21. The pellets are then cast in place with a binder or composite matrix.

(C) Pellets of AP, TFTA, and AP/boron combinations have been successfully tested. Other pelletized combinations such as TFTA/AP and boron/AP are impact sensitive in certain ratios and therefore cannot be used.

(C) Both coated and uncoated pellets have been cast in 5.0 fuel grains and have been tested. Pellet and particle coatings, discussed in the following section, are applied to inhibit interfacial contact and thereby reduce the tendency to sustain combustion.

d. Physical Properties

(U) The fuel system to be used in full-scale motor development was subjected to additional testing to determine its physical properties. These properties are listed for two cure periods as follows:

With 42-hr Cure at 140°F	After Additional Cure of 31 hr at 175°F
ρ = 0.0464 lb/in.^{3}	ρ = 0.0462 lb/in.^{3}
Tensile - 148 psi	Tensile - 188 psi
Elongation - 39%	Elongation - 32%
Autoignition - 625°F	Autoignition - 615°F
Drop hammer impact - 25.8 kg-cm	Drop hammer impact - 23.6 kg-cm

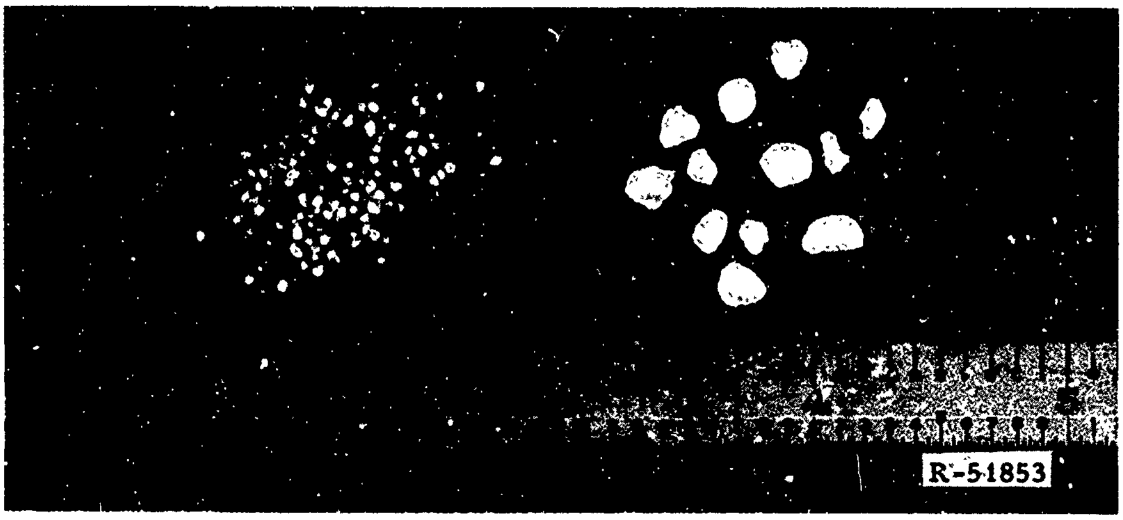

Figure 16. (U) AP Particles

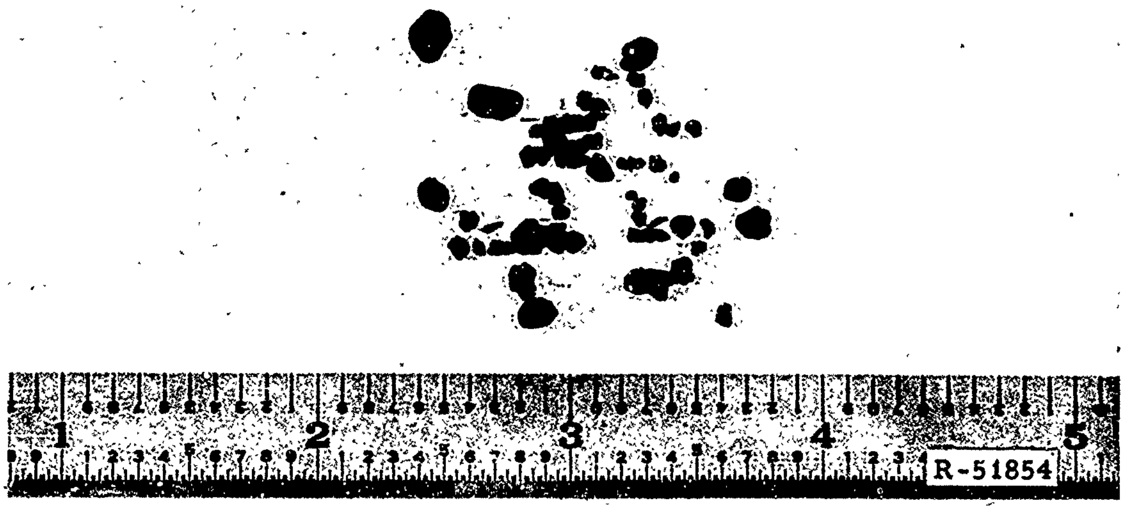

Figure 17. (U) Boron/AP Particles

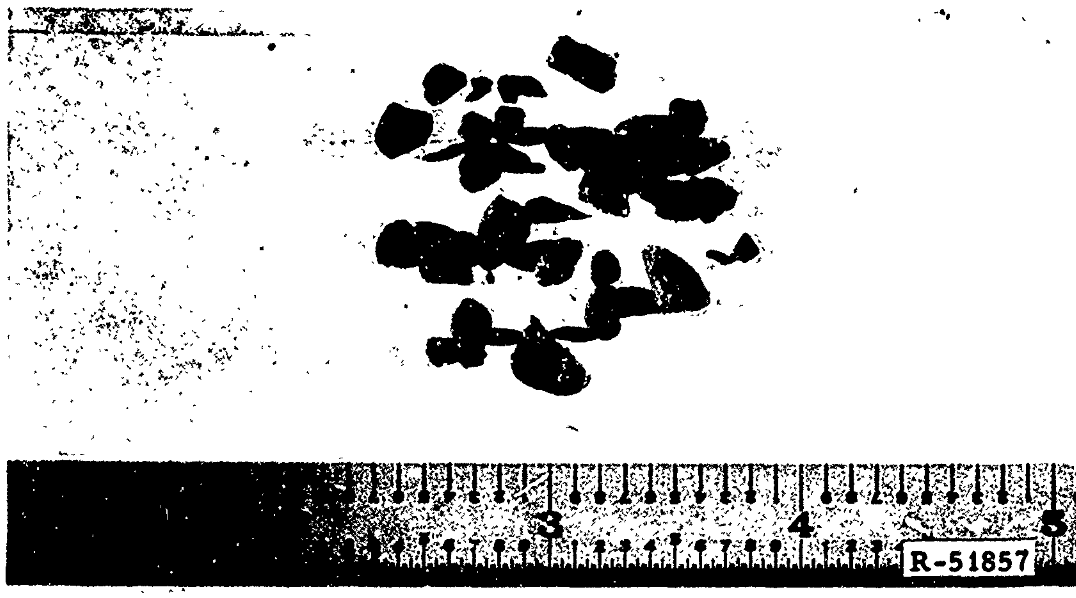

Figure 18. (U) Boron/TFTA Particles

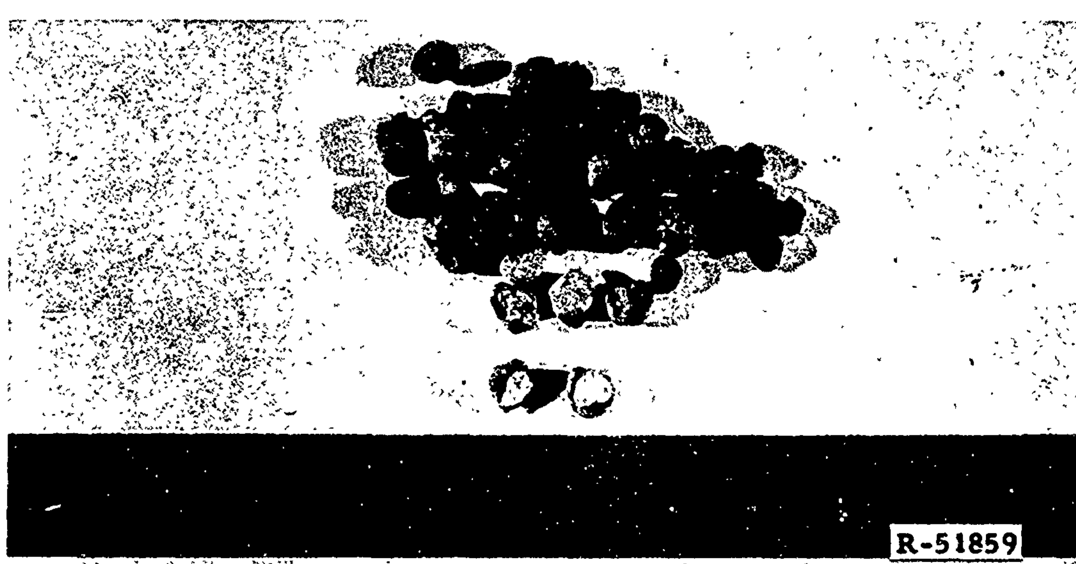

Figure 19. (U) AP Particles Coated with Boron and TFTA

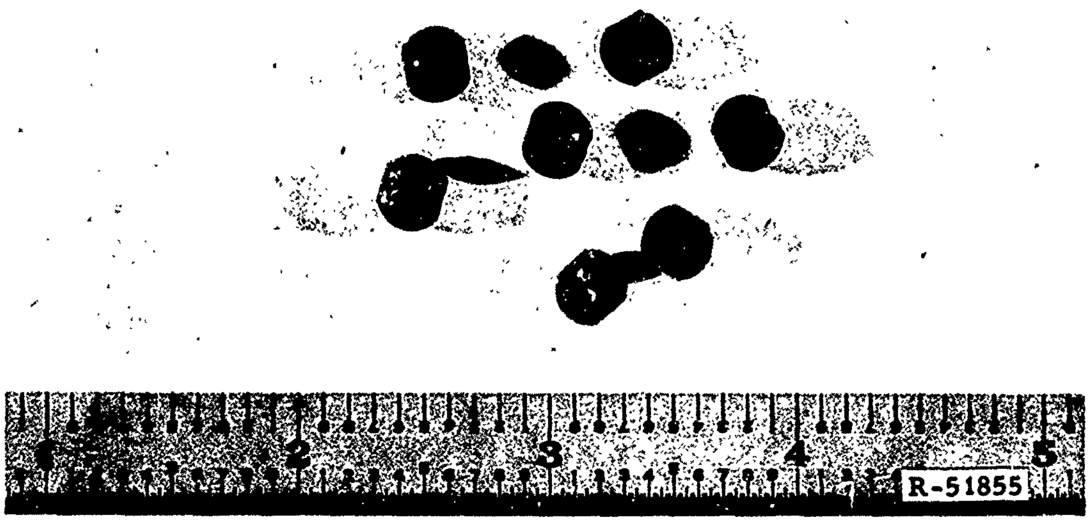

Figure 20. (U) Boron/AP Pellets Coated with Kel-F

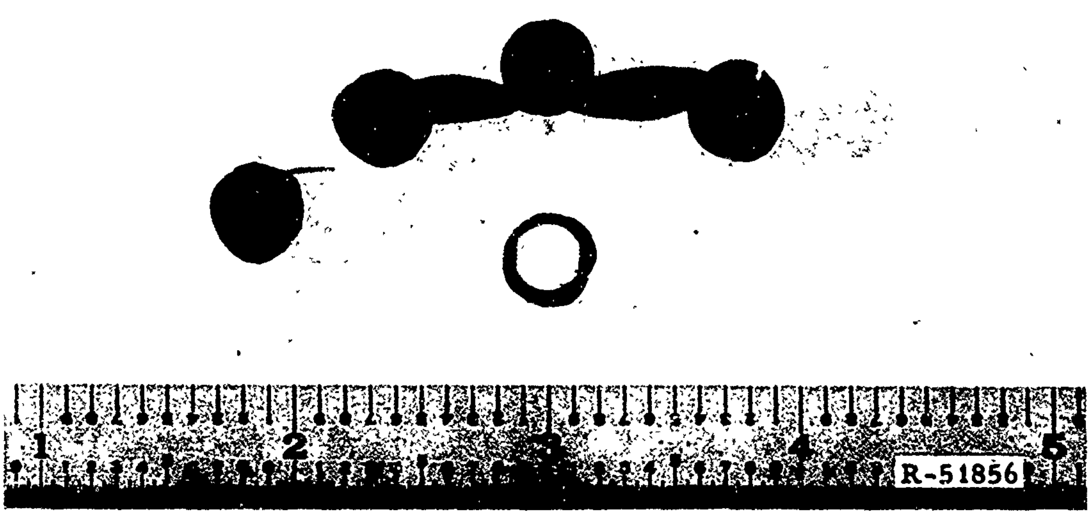

Figure 21. (U) AP Pellets Coated with Boron

(U) Naval Ordnance Laboratory (NOL) detonation card gap tests were conducted to further investigate the impact sensitivity of the fuel. The tests resulted in no detonations with zero cards, thus indicating the fuel to be insensitive to impact. The NOL card gap tests are recognized to be a more accurate means of determining the detonability of propellants. Procedures for NOL card gap tests are outlined in "Explosives Hazards Classification Procedures" issued by the Air Force as technical order TO-11A-1-47.

e. Combustion Studies

(U) Hybrid fuel combustion studies were conducted to evaluate the combustion characteristics of candidate fuel systems. Tests were conducted with a 1-in. laboratory survey motor, shown in figure 22, to determine the nonsustaining character of fuels and to determine the influence of each fuel ingredient. Additional testing was conducted with an optical bomb, shown in figure 23, to evaluate large particle fuel ingredients and their coatings which could not be evaluated in the laboratory survey motor.

(C) The studies have shown that nonsustaining fuels with up to 40% AP can be produced and that the addition of boron to the fuel tends to diminish that limit. The optical bomb studies predict the nonsustaining characteristics of fuels with large particles or pellets.

(U) The studies were initiated after subscale motor tests of candidate fuels failed to produce a suitable nonsustaining fuel system. The problem which is discussed later was attributed to the QX/DER binder system, but in solving the problem it became apparent that the sustaining characteristics of a fuel were not easily identifiable from subscale motor tests. The following discussion will serve to describe the problem of identifying the sustaining characteristics of a fuel.

(U) A highly loaded AP/binder fuel is a solid propellant and clearly will sustain combustion after termination of

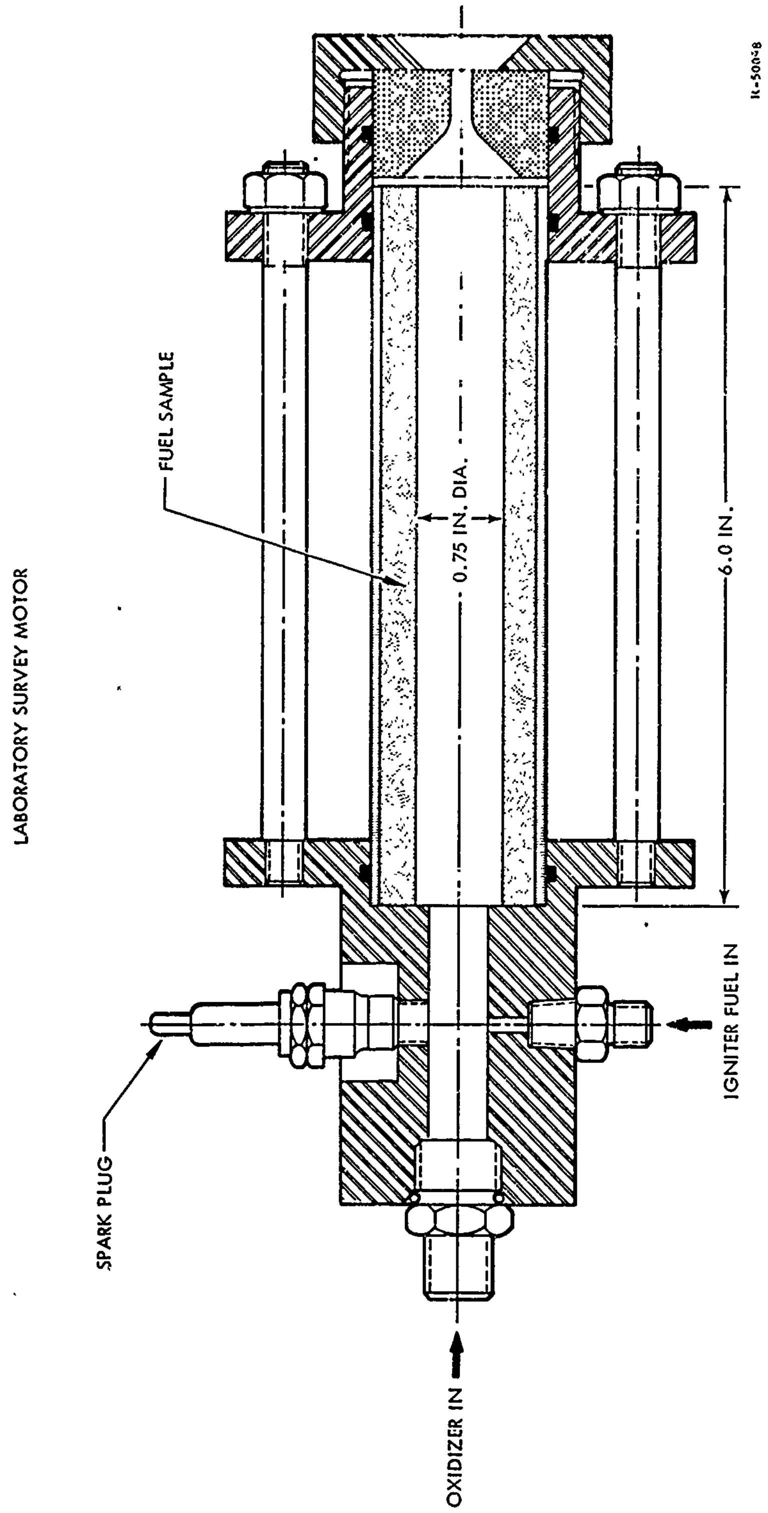

Figure 22. (U) Laboratory Survey Motor

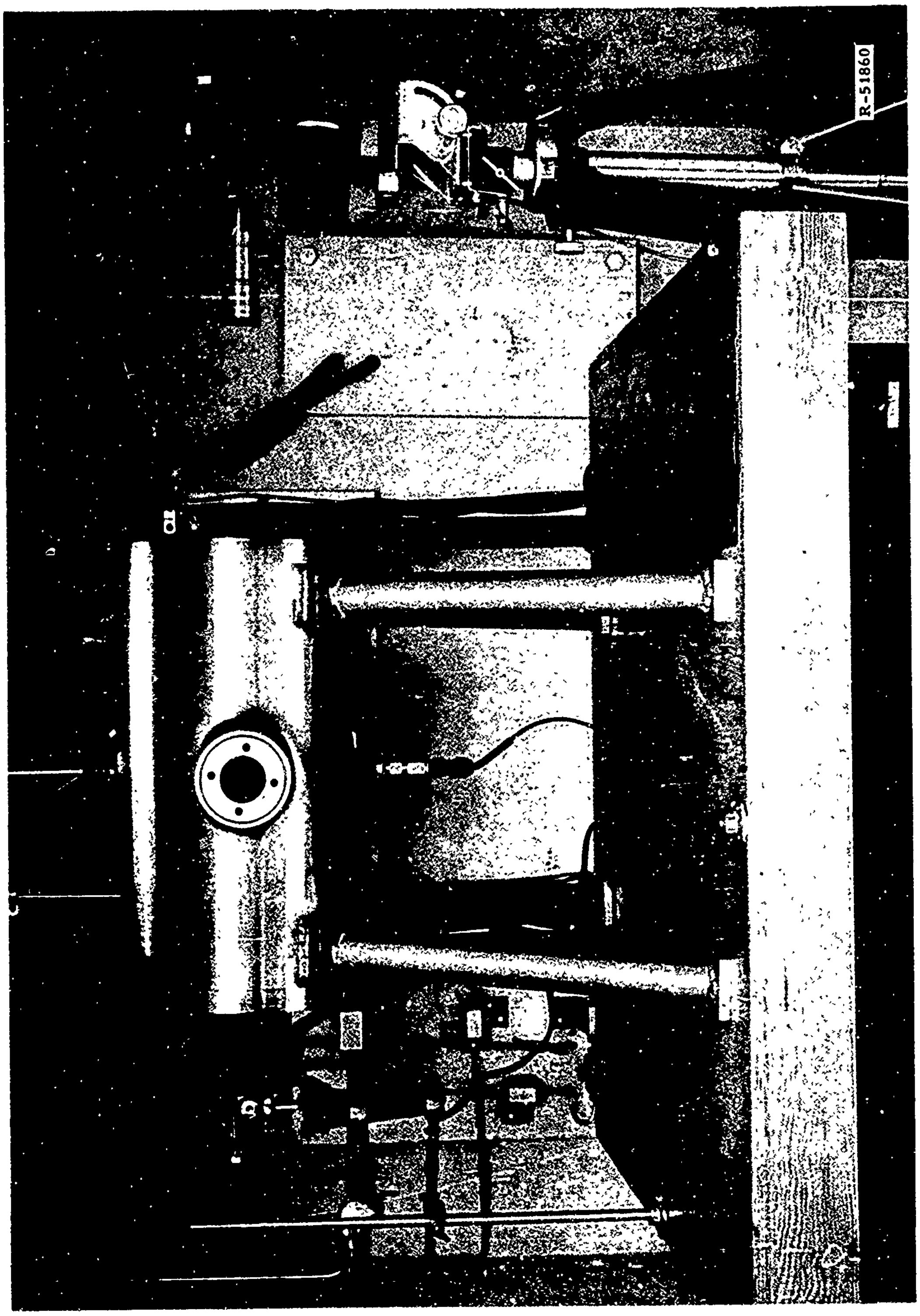

Figure 23. (U) Optical Bomb

oxidizer flow when used as hybrid fuel. It is also evident that hydrocarbon binder, with no oxygen-containing additives, will not sustain combustion when enclosed in a motor case. However, most advanced hybrid fuels use oxygen-containing or other reactive additives which place the fuel between these limits of sustaining and nonsustaining characteristics. Under certain circumstances these fuels may sustain combustion, and under other circumstances, they appear to sustain combustion when, in fact, they do not.

(U) The best definition of a nonsustaining fuel is one which permits abrupt termination of thrust and which also does not continue to consume or degrade itself after oxidizer flow is terminated. Even pure binder can appear to sustain combustion if large quantities of graphite and non-ablative insulation materials are used in the construction of the motor. These materials, which can absorb heat during the firing, can radiate or conduct energy to the adjacent fuel or insulation materials after the firing. Volatilization of fuel and insulation then results until the motor components are sufficiently cool. Meanwhile, reaction of the volatiles with air outside the motor gives a false impression of continued internal combustion, the duration of which is dependent on the size and type of heat absorbing materials used.

(C) An example of this apparent sustained combustion are three 5.0-in. motor tests (Nos. 342, 344, and 345, table IX) in which the fuels were (No. 342) 100% R-binder; (No. 344) 20% boron, 10% AP, and 70% R-binder; and (No. 345) 50% TFTA and 50% R-binder. In test No. 342, after abrupt and complete thrust termination, external combustion continued at the nozzle for 8 sec and smoke continued to billow from the nozzle for 8 additional sec. In each case of tests No. 344 and No. 345, smoke continued to exhaust from the nozzle for approximately 15 sec, and again no thrust or chamber pressure was recorded. Postfire inspection of the fuel grains revealed no evidence of sustained combustion. Since no reactive products could originate from the fuel in tests No. 342 and

TABLE IX

(U) SUMMARY OF 5.0-IN. MOTOR TESTS

Test Number	Fuel: TFTA	Fuel: Boron	Fuel: AP	Fuel: R-Binder	Oxidizer	P_c (psi)	$\dot{w}_{ox}$ (lb/sec)	t_b (sec)	Mixer	Comments
Series III										
L40342	---	---	---	100	ClF_3	670	1.15	10	Graphite	External combustion 8 sec; did not sustain
L40343	---	---	---	100	ClF_3	670	1.15	3	Graphite	Smoke 10 to 15 sec; did not sustain
L40344	---	20	10	70	ClF_3	750	1.14	10	Graphite	Smoke 10 to 15 sec; did not sustain
L40345	50	---	---	50	ClF_3	680	1.14	10	Graphite	Smoke 15 sec; did not sustain
L40365	30	5	30	35	ClF_3	100	0.5	13	Graphite	Some posttest smoke; did not sustain
L40366	30	---	30	40	ClF_3	100	0.5	20	Graphite	Some posttest smoke; did not sustain
L40367	30	---	30	40	ClF_3	100	1.5/0.16	15	Graphite	Some posttest smoke; used aft injection
L40368	30	5	30	35	ClF_3	275	1.8/0.17	20	Graphite	Some posttest smoke; used aft injection
L40369	30	---	30	40	ClF_3	320	1.8/0.17	20	Graphite	Some posttest smoke; used aft injection
K-17A-1	30	5	30	35	ClF_3	195	0.51	29	Graphite	External combustion
H-17A-2	30	5	30	35	ClF_3	148	0.51	29	Composite	Less posttest smoke
H-17A-3	30	5	30	35	ClF_3	172	0.51	30	None	Clean shutoff; no smoke
H-17A-4	25	15	35	25	ClF_3	900	1.0	20	Graphite	Clean shutoff; reignited after 10 sec
H-17A-5	16	8	56	20	ClF_3	900	1.5	5	Composite	Pelletized fuel; sustained combustion
H-17A-6	---	15	35	50	ClF_3	900	1.0	20	Composite	Some external combustion
H-17A-7	22.5	15	35	27.5	ClF_3	900	1.0	10	Composite	Some external ccmbustion
Series IV										
L40346	50	---	---	50	ClF_3	700	1.8/0.2	1.3	Graphite	Fuel characterization
L40347					ClF_3	700	1.8/0.2	2.2		
L40348					ClF_3	700	1.8/0.2	20		
L40349					ClF_3	700	1.8/0.2	1.3		
L40350					ClF_3	580	1.8/0.2	10		
L40351					ClF_3	455	1.8/0.2	20		
L40352					ClF_3	430	1.8/0.2	20		
L40353					ClF_3	630	1.8.0.2	15		
L40354					ClF_3	630	1.8/0.2	2		
L40355					ClF_3	700	1.8	7		
L40356					ClF_3	425	1.0	30		
L40357					ClF_3/ClO_3F	---	0.51	35		
L40358					ClF_3/ClO_3F	---	0.5	20		
L40359					ClF_3/ClO_3F	---	0.5	20		
L40360					ClF_3/ClO_3F	---	0.5	20		
L40361					ClF_3/ClO_3F	---	2.0	15		
L40362					ClF_3/ClO_3F	---	2.0	1.5		
L40363					ClF_3/ClO_3F	---	1.4	35		
L40364	50	---	---	50	ClF_3/ClO_3F	---	1.4	---	Graphite	Fuel characterization

No. 345, the smoke can be attributed only to transient volatilization of the fuel by means of heat loads imposed by the mixer.

(C) When oxygen-containing fuel ingredients are used, the additional heat radiated from hot motor components is sometimes sufficient to volatize the binder and additives and permit continued internal combustion. Therefore, a normally nonsustaining fuel may become a self-sustaining fuel when subjected to these additional heat loads. Tests H17A-1, 2, and 3 were conducted with the fuel containing 30% TFTA, 5% boron, 30% AP, and 35% R-binder, which was selected for full-scale motor development and was known to be nonsustaining in laboratory tests. Using a graphite mixer in test No. 1, the fuel sustained combustion after termination of oxidizer flow. Again no thrust and chamber pressure were recorded, although smoking continued for more than 30 sec. Posttest inspection showed degradation of the fuel especially near the mixer assembly with some unburned fuel remaining at the injector end of the motor. A composite mixer of ablative materials and graphite was used in the subsequent test and no mixer at all was used in the third test. Neither motors sustained combustion although some posttest smoke was generated in motor No. 2. No evidence of volatilization occurred with motor No. 3.

(C) The apparent and actual sustaining tendency is further aggravated by use of high loading levels of boron in homogeneous fuel blends. Boron increases the conductivity of the fuel, causing a temperature increase in the fuel sublayers which results in increased volatilization of the fuel components.

(U) If the volatile components are not reactive, the result is the extension of postfire smoke generation, with the possible development of a hard sintered boron structure in the fuel grain. If the fuel contains oxygen, the ensuing reaction at the fuel surface may not be intense but can in some cases liberate sufficient heat to prolong combustion until all or part of the fuel is consumed or degraded. In this case, the boron sintered structure receives energy from the reactants, and returns it by conduction to the unburned fuel sublayers to propagate the reaction.

(C) It was theorized and later discovered to be true that higher regression rates would tend to suppress the tendency to sustain combustion. The motor of test No. H-17A-7 used a fuel containing 25% TFTA, 15% boron, 35% AP, and 25% binder with graphite and phenolic mixer parts. The motor terminated thrust and chamber pressure on termination of oxidizer flow without post-test smoke generation, but after approximately 10 sec heat loads imposed on the fuel by the mixer components were sufficient to reignite the motor. The test indicates that higher regression rates tend to inhibit sustaining characteristics. The fuel contained higher AP and boron levels than did the other fuels and yet shut off without postfire combustion or smoke. The rapid termination of combustion can be attributed only to having cooler fuel surface sublayers as a result of the high regression rate of this fuel. Self-ignition of the motor after shutdown indicates the intensity of the heat loads emanating from the mixer.

(C) Sustained combustion will result from an exothermic reaction of the fuel components at the grain surface. Of the fuel components used, only AP has the capacity to react with sufficient energy to cause sustained combustion in this manner without externally applied heat loads. However, the loading limit of AP without sustaining has been well established at 40% for coarse particle AP and 15% for "as received" AP. The boron loading limit has also been established and the sustaining combustion problem has been resolved in propellant development studies with respect to the fuel alone. The problem now extends into the area of engineering design and materials selection for full-scale motor components as well. The problem will be finally resolved in full-scale motor configurations, since only in the full-scale motor can design and material selection be simultaneously applied.

(C) As result of the combustion studies, three nonsustaining castable fuel systems were selected for possible application to full-scale motor development testing. The nonsustaining fuels are listed as follows:

A	30% TFTA	5% Boron	30% AP	34% R-binder
B*	25% TFTA	15% Boron	35% AP	25% R-binder
C†	22.5% TFTA	15% Boron	35% AP	27.5% R-binder

* In both fuels, boron and TFTA were included in the form of large particles.
† Fuel C is similar to fuel B but uses increased binder content to improve castability.

(C) Fuel B is similar to fuel A with the exception of the boron content. Since fuel A is of superior performance, further consideration of the fuel B is unnecessary.

(C) The tests indicate that the higher performance fuel B may be suitable for use now in full-scale motor development. Its nonsustaining character must be verified in full-scale motor designs which minimize heat loads from nozzle and mixer components. However, at the present time, the full-scale motor development effort requires a fuel which will not sustain under the most adverse conditions; therefore, fuel A was selected.

f. Laboratory Studies

(C) A total of 79 laboratory motor tests were conducted to determine the sustaining characteristics of TFTA, boron, AP, and R-binder-containing fuels without the heat flux effects normally contributed by motor components in subscale (5.0 in.) tests. The tests were conducted with the motor shown in figure 22 and used gaseous oxygen as oxidizer at a flow rate of 0.01 lb/sec. The tests which are listed in table X were designed to evaluate the effects of each fuel component on the sustaining characteristics of the fuel blend. The formulation variables which affect the combustion characteristics include the content, particle size, total solids loading, and type of precompacted particles.

(C) A significant development was achieved with the discovery that formulations containing 40% AP are nonsustaining, so long as the AP particle size is large (at least 600μ to 800μ) and the boron content in the binder matrix is kept low (10% or less).

(C) The nonsustaining AP loading limit had previously been established at approximately 15%, using "as received" AP which was nominally 175μ size. The tests indicate that no significant increase in the AP loading limit is obtained by increasing the AP particle size from 800μ.

(C) It is evident that the AP loading limit is significantly affected by boron content but not the TFTA content of the fuel. With high boron content in the binder matrix, the fuel conductivity is significantly increased and as a result the fuel sublayers become very hot during combustion, thus vaporizing the volatile components until the available energy is used and the unburned fuel returns to a lower temperature. This condition was eliminated in some compositions containing boron by precompacting boron in prills or chunks with either TFTA or AP thereby removing it from the binder matrix.

TABLE X

(U) 1.0-in. MOTOR TESTS

Test No.	Binder R-45 1.0 TDI 1.2 %	TFTA (Dried) CLIN %	AP 600/800μ %	Boron Bimodel Dried %	$\dot{w}_{ox}$ lb/sec	Duration sec	P_c psig	Fuel Weight Loss g	Nozzle Size	Sustain	$\dot{w}_f$ g/sec
1	55.0	---	5.0	40.0	0.01	5	5	3.9	0.25	No	---
2	50.0	---	10.0	40.0	0.01	5	6	5.0	0.25	No	---
3	45.0	---	15.0	40.0	0.01	5	8	21.9	0.25	Yes	---
4	55.0	---	5.0	40.0	0.01	5	160	6.47	0.0935	No	---
5	50.0	---	10.0	40.0	0.01	5	160	12.15	0.0935	No	---
6	45.0	---	15.0	40.0	0.01	5	160	25.3	0.0935	Yes	---
7	40.0	---	Drilled 20.0	40.0	0.01	3	175	21.6	0.0935	Yes	---
8	40.0	---	20.0	40.0	0.01	2	---	28.2	0.0935	Yes	---
9	40.0	---	20.0	40.0	0.01	3	145	26.9	0.0935	Yes	--
10	40.0	---	Drilled 20.0	40.0	0.01	3	180	15.9	0.0935	Yes	---
11	35.0	---	25.0	40.0	0.01	3	180	29.4	0.0935	Yes	---
12	50.0	50.0	---	---	0.01	3	60	5.4	0.157	No	1.8
13	50.0	50.0	---	---	0.01	5	60	8.3	0.157	No	1.66
14	40.0	30.0	30.0	---	0.01	3	100	14.4	0.160	No	4.8
15	40.0	30.0	30.0	---	0.01	3	100	14.2	0.160	No	4.73
16	45.0	35.0	20.0	---	0.01	4	90	13.4	0.160	No	4.48 {0.0097 lb/sec
17	45.0	35.0	20.0	---	0.01	4	85	13.7	0.160	No	4.22
18	43.0	(B) Granules	24.0	33.0	0.01	3	125	---	0.160	Yes	---
19	Void	---	---	---	---	---	---	---	---	---	---
20	37.8	(D) Granules	28.3	33.9	0.01	3	150	---	0.160	Yes	---
21	Void	---	---	---	---	---	---	---	---	---	---
22	38.6	(C) Granules	37.2	24.2	0.01	Blew Nozzle →			Nozzle Plug	---	---
23	40.0	30.0	30.0	---	0.01	5	140	21.8	0.157	No	4.04
24	25.0	30.0	30.0	5.0	0.01	5	155	28.6	0.157	No	5.72 {0.0126 lb/sec

Test No.	Binder R-45/TDI %	TFTA (Dried) %	AP %	Boron %	$\dot{w}_{ox}$ lb/sec	Duration sec	P_c psig	Fuel Weight Loss g	Sustain	Ratio Type Granules Boron/TFTA	Granules %
25	40.0	30.0	30.0	---	0.01	3	100	13.4	No	---	---
26	35.0	30.0	30.0	5.0	0.01	3	85	14.3	No	1/2	15.0
27	35.0	30.0	30.0	5.0	0.01	3	85	15.7	No	1/2	15.0
28	35.0	30.0	30.0	5.0	0.01	3	85	18.6	No	1/2	15.0
29	30.0	30.0	30.0	10.0	0.01	3	85	18.9	No	1/2	30.0

30	35.0	25.0	40.0	---	0.01	3	100	13.6	No	---	---
[illegible]											
19	Void	---	---	---	---	---	---	---	---	---	---
20	37.8	(D) Granules	28.3	33.9	0.01	3	150	---	0.160	Yes	---
21	Void	---	---	---	---	---	---	---	---	---	---
22	38.6	(C) Granules	37.2	24.2	0.01	Blew Nozzle			Nozzle Plug	---	---
23	40.0	30.0	30.0	---	0.01	5	140	21.8	0.157	No	4.04
24	25.0	30.0	30.0	5.0	0.01	5	155	28.6	0.157	No	5.72 0.0126 lb/sec

Test No.	Binder R-45/TDI %	TFTA (Dried) %	AP %	Boron %	$\dot{w}_{ox}$ lb/sec	Duration sec	P_c psig	Fuel Weight Loss g	Sustain	Ratio Type Granules Boron/TFTA	Granules %
25	40.0	30.0	30.0	---	0.01	3	100	13.4	No	---	---
26	35.0	30.0	30.0	5.0	0.01	3	85	14.3	No	1/2	15.0
27	35.0	30.0	30.0	5.0	0.01	3	85	15.7	No	1/2	15.0
28	35.0	30.0	30.0	5.0	0.01	3	85	18.6	No	1/2	15.0
29	30.0	30.0	30.0	10.0	0.01	3	85	18.9	No	1/2	30.0
30	35.0	25.0	40.0	---	0.01	3	100	13.6	No	---	---
31	40.0	30.0	30.0	---	0.01	3	100	12.9	No	---	---
32	35.0	30.0	30.0	5.0	0.01	3	85	15.8	No	1/2	15.0
33	30.0	30.0	30.0	10.0	0.01	3	85	18.9	No	1/2	30.0
34	35.0	25.0	40.0	---	0.01	3	100	19.0	No	---	---
35	30.0	15.0	40.0	15.0	0.01	3	110	48.6	Yes	---	---
36	30.0	15.0	40.0	15.0	0.01	3	90	49.1	Yes	---	---
37	30.0	15.0	40.0	15.0	0.01	2	100	49.6	Yes	---	---
38	55.0	5.0	40.0	---	0.01	3	75	17.7	No.	---	---
39	55.0	5.0	40.0	---	0.01	3	75	14.7	No	---	---
40	50.0	10.0	40.0	---	0.01	3	85	16.6	No	---	---
41	50.0	10.0	40.0	---	0.01	3	75	20.0	No	---	---
42	45.0	15.0	40.0	---	0.01	3	65	17.8	No	---	---
43	45.0	15.0	40.0	---	0.01	3	60	18.4	No	---	---
44	40.0	20.0	40.0	---	0.01	3	60	18.4	No	---	---
45	40.0	20.0	40.0	---	0.01	3	50	12.1	No	---	---
46	30.0	20.0	40.0	10.0	0.01	3	90	23.7	No	---	---
47	30.0	20.0	40.0	10.0	0.01	2	90	17.2	No	---	---
48	30.0	25.0	40.0	5.0	0.01	3	75	18.7	No	---	---
49	30.0	25.0	40.0	5.0	0.01	2	65	9.0	No	---	---
50	25.0	20.0	40.0	15.0	0.01	3	100	49.4	Yes	---	---
51	25.0	20.0	40.0	15.0	0.01	3	100	49.5	Yes	---	---
52	25.0	30.0	30.0	15.0	0.01	3	120	37.1	No	1/2	45.0
53	25.0	30.0	30.0	15.0	0.01	2	150	33.1	No	1/2	45.0
54	30.0	30.0	30.0	10.0	0.01	2	65	7.1	No	---	---
55	30.0	30.0	30.0	10.0	0.01	3	65	13.3	No	---	---
56	30.0	25.0	30.0	15.0	0.01	3	75	14.8	No	---	---
57	30.0	25.0	30.0	15.0	0.01	3	75	15.2	No	---	---
58	25.0	25.0	35.0	15.0	0.01	3	85	18.0	No	---	---
59	25.0	25.0	35.0	15.0	0.01	3	85	19.4	No	---	---
60	30.0	20.0	35.0	15.0	0.01	3	80	16.7	No	---	---
61	30.0	20.0	35.0	15.0	0.01	3	80	16.2	No	---	---
62	30.0	20.0	40.0	10.0	0.01	3	105	24.7	No	1/2	30.0
63	30.0	20.0	40.0	10.0	0.01	3	120	32.0	No	1/2	30.0
64	30.0	25.0	30.0	15.0	0.01	3	70	27.1	No	1/2	30.0
65	30.0	25.0	30.0	15.0	0.01	3	75	18.6	No	1/2	30.0
66	25.0	30.0	30.0	15.0	0.01	3	75	18.7	No	1/2	30.0
67	25.0	30.0	30.0	15.0	0.01	3	75	17.4	No	1/2	30.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Yes	1/2	30.0

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31	40.0	30.0	30.0	---	0.01	3	100	12.9	No	---	---
32	35.0	30.0	30.0	5.0	0.01	3	85	15.8	No	1/2	15.0
33	30.0	30.0	30.0	10.0	0.01	3	85	18.9	No	1/2	30.0
34	35.0	25.0	40.0	---	0.01	3	100	19.0	No	---	---
35	30.0	15.0	40.0	15.0	0.01	3	110	48.6	Yes	---	---
36	30.0	15.0	40.0	15.0	0.01	3	90	49.1	Yes	---	---
37	30.0	15.0	40.0	15.0	0.01	2	100	49.6	Yes	---	---
38	55.0	5.0	40.0	---	0.01	3	75	17.7	No.	---	---
39	55.0	5.0	40.0	---	0.01	3	75	14.7	No	---	---
40	50.0	10.0	40.0	---	0.01	3	85	16.6	No	---	---
41	50.0	10.0	40.0	---	0.01	3	75	20.0	No	---	---
42	45.0	15.0	40.0	---	0.01	3	65	17.8	No	---	---
43	45.0	15.0	40.0	---	0.01	3	60	18.4	No	---	---
44	40.0	20.0	40.0	---	0.01	3	60	18.4	No	---	---
45	40.0	20.0	40.0	---	0.01	3	50	12.1	No	---	---
46	30.0	20.0	40.0	10.0	0.01	3	90	23.7	No	---	---
47	30.0	20.0	40.0	10.0	0.01	2	90	17.2	No	---	---
48	30.0	25.0	40.0	5.0	0.01	3	75	18.7	No	---	---
49	30.0	25.0	40.0	5.0	0.01	2	65	9.0	No	---	---
50	25.0	20.0	40.0	15.0	0.01	3	100	49.4	Yes	---	---
51	25.0	20.0	40.0	15.0	0.01	3	100	49.5	Yes	---	---
52	25.0	30.0	30.0	15.0	0.01	3	120	37.1	No	1/2	45.0
53	25.0	30.0	30.0	15.0	0.01	2	150	33.1	No	1/2	45.0
54	30.0	30.0	30.0	10.0	0.01	2	65	7.1	No	---	---
55	30.0	30.0	30.0	10.0	0.01	3	65	13.3	No	---	---
56	30.0	25.0	30.0	15.0	0.01	3	75	14.8	No	---	---
57	30.0	25.0	30.0	15.0	0.01	3	75	15.2	No	---	---
58	25.0	25.0	35.0	15.0	0.01	3	85	18.0	No	---	---
59	25.0	25.0	35.0	15.0	0.01	3	85	19.4	No	---	---
60	30.0	20.0	35.0	15.0	0.01	3	80	16.7	No	---	---
61	30.0	20.0	35.0	15.0	0.01	3	80	16.2	No	---	---
62	30.0	20.0	40.0	10.0	0.01	3	105	24.7	No	1/2	30.0
63	30.0	20.0	40.0	10.0	0.01	3	120	32.0	No	1/2	30.0
64	30.0	25.0	30.0	15.0	0.01	3	70	27.1	No	1/2	30.0
65	30.0	25.0	30.0	15.0	0.01	3	75	18.6	No	1/2	30.0
66	25.0	30.0	30.0	15.0	0.01	3	75	18.7	No	1/2	30.0
67	25.0	30.0	30.0	15.0	0.01	3	75	17.4	No	1/2	30.0
68	25.0	20.0	40.0	15.0	0.01	3	155	45.9	Yes	1/2	30.0
69	25.0	20.0	40.0	15.0	0.01	1.5	160	45.6	Yes	1/2	30.0
70	25.0	25.0	35.0	15.0	0.01	3	90	23.1	No	1/1	30.0
71	25.0	25.0	35.0	15.0	0.01	3	85	23.8	No	1/1	30.0
72	25.0	25.0	35.0	15.0	0.01	3	105	30.0	No	1/1	20.0
73	25.0	25.0	35.0	15.0	0.01	2	100	18.9	No	1/1	20.0
74	30.0	20.0	35.0	15.0	0.01	3	85	23.3	No	1/1	20.0
75	30.0	20.0	35.0	15.0	0.01	3	85	24.5	No	1/1	20.0
76	27.5	22.5	35.0	15.0	0.01	2	80	15.1	No	1/1	20.0
77	27.5	22.5	35.0	15.0	0.01	3	80	21.1	No	1/1	20.0
78	25.0	25.0	35.0	15.0	0.01	3	80	22.3	No	1/1	20.0
79	25.0	25.0	35.0	15.0	0.01	3	80	23.8	No	1/1	20.0

(C) The following formulations represent the upper loading limits of AP in fuel blends containing various percentages of boron while retaining nonsustaining combustion characteristics.

AP %	Boron %	TFTA %	R-Binder %
40	10	20	30
35	15	20	30

(C) More than 40% AP in the matrix without any boron will result in a sustaining fuel. By putting the boron and TFTA in particle form, the concentration of AP in the matrix is increased above the maximum level and therefore results in sustained combustion although no boron may be included in the matrix itself.

1. Optical Bomb Studies

(U) Optical bomb studies were conducted to determine the mechanism of sustaining fuel systems and to determine means of preventing this phenomenon in highly loaded large particle fuel systems.

(U) The optical bomb shown in figure 24 consists of a high-pressure container with a viewing window in which small solid propellant samples can be burned. With this instrument, high-pressure nitrogen and an adjustable exhaust valve can be used to evaluate hybrid fuel samples at operating pressures up to 2,000 psi.

(U) For evaluation of hybrid fuels, samples 1 in. by 1 in. by 2 in. are placed in the bomb adjacent to solid-propellant charges. The flame from the solid propellant, which is ignited by hot wires, is directed onto the surface of the hybrid fuel grain. The behavior of the fuel sample is then viewed after the solid-propellant charge is exhausted.

2. QX/DER Binder Evaluation

(C) Initial tests conducted with the optical bomb were made with fuels containing TFTA, boron, AP, and QX/DER binder in essentially the same formulation as that used in earlier 3.5-in.-diameter motor tests where sustained combustion had occurred. The AP loading levels in these tests were as low as 5%. The optical bomb tests, described in the following paragraphs, tend to confirm the results of the 3.5-in.-diameter motor tests, which indicate that heat loads imposed by the motor components were (in this case) not responsible for the sustaining character of the fuels.

(U) The initial tests exposed the four-component hybrid fuel to the flame from a strip of solid propellant at various pressures. If the samples ignited, the bomb was depressurized and the pressure at which point combustion terminated was noted. The results are given in table XI. It was found that all formulations having AP levels ranging from 7.5% to 15% sustained combustion. All the propellant samples except one sustained at a pressure below 100 psi, and it is probable the same thing would happen in a motor fuel grain configuration without the heat input from surrounding hot motor components.

(U) The sustaining reaction of these formulations is not typical of solid propellants; there is no flame, but there is a considerable amount of smoke and ejection of some white-hot metal particles at higher pressures. The reaction, which can be described as a fizzing reaction, reduces the binder to a gummy sinter. The residual material in these tests did not become red hot.

3. Studies with Particles, Pellets and Coatings

(U) Optical bomb studies were also conducted with fuels containing either large particles or pellets to evaluate the nonsustaining character of highly loaded propellants. These fuel samples were similar to the ones shown in figures 24 and 25. The results of the studies are listed in table XI.

(U) These tests included evaluation of pellets and various particles sizes. Coating techniques were also involved, as were variations in the matrices of the test samples. The optical bomb studies are not known to reproduce exactly the conditions of subscale motor tests. It can be said, however, that fuels which would sustain combustion in optical bomb tests would certainly sustain combustion in motor tests.

(C) Large particles or pellets provide a means of including AP, AP and boron, or boron and TFTA into a fuel grain similar to the one shown in figure 13 with solids loading in excess of 80%. The formulation of a fuel containing only 20% binder greatly increases the number of available high-performance fuels.

TABLE XI

(U) OPTICAL BOMB STUDIES

Test	Type Particle	Pellet Formulation TFTA	Pellet Formulation Boron	Pellet Formulation AP	Pellet Formulation Binder	Pellet Formulation Al	Pellet Formulation Total %	Coating	Total %	Matrix Formulation TFTA	Matrix Formulation Boron	Matrix Formulation AP	Matrix Formulation Binder	Matrix Formulation Total %	Comment
1	Pellet 1/4 in.	35	–	62	3	–	60	Thin KEL-F	2	55	–	–	45	38	Pellet separation by KEL-F coating - intense flame oxidizer binder - matrix decomposed - sustained combustion
2		–	–	62	3	35	–	Thin KEL-F	2	55	–	–	45	38	Aluminum substituted for boron in pellets - did not sustain combustion
3		–	17	62	3	17	–	Thin KEL-F	2	55	–	–	45	38	Blended aluminum and boron - sustained combustion
4		–	35	60	5	–	60	R-Binder	6	–	24	36	40	34	2% tricresylphosphate added to pellet binder - sustained boron and AP loading too high
5		–	37	58	3	–	60	R-Binder	6	–	46	–	54	34	Did not sustain
6	Particle 1/16 to 1/8 in.	–	37	60	3	–	50	R-Binder	4	–	46	–	54	46	Sustained - this coating could not contain hot particle flame - boron content in matrix high
7	Pellet	–	35	60	5	–	48	TFTA	12	34	8	16	42	40	Sustained - high AP loading in matrix
8		–	–	100	–	–	40	Boron	20	–	40	–	60	40	Did not sustain
9		–	35	60	5	–	48	TFTA	12	–	24	36	50	40	Sustained - high AP and boron loading in matrix
10		–	–	100	–	–	40	Boron	20	–	–	–	100	40	Did not sustain - boron coating formed hard shell which did not burn
11		–	–	100	–	–	40	Boron	20	25	–	–	75	40	Did not sustain - boron coating formed hard shell which did not burn
12		–	–	100	–	–	40	Boron	20	–	–	25	75	40	Did not sustain - boron coating formed hard shell which did not burn
13		–	–	100	–	–	40	Boron	20	20	20	–	60	40	Did not sustain - boron coating formed hard shell which did not burn
14		–	–	100	–	–	40	Boron + TFTA	20	–	–	–	100	40	Did not sustain - effective coating - burns clean
15		–	–	100	–	–	40	Boron + TFTA	20	–	10	–	90	40	Did not sustain - effective coating - burns clean
16		–	–	100	–	–	40	Boron + TFTA	20	29	–	33	38	40	Did not sustain - effective coating - burns clean
17		–	–	100	–	–	40	Boron + TFTA	20	25	–	37	38	40	Did not sustain - effective coating - burns clean
18		–	–	100	–	–	40	Boron + TFTA	20	13	–	37	50	40	Did not sustain - effective coating - burns clean

TABLE XI

(U) OPTICAL BOMB STUDIES (Continued)

		Pellet Formulation								Matrix Formulation					
Test	Type Particle	TFTA	Boron	AP	Binder	Al	Total %	Coating	Total %	TFTA	Boron	AP	Binder	Total %	Comment
19	Agglomerate .050 to .125 in.	–	–	100	–	–	25	Boron + TFTA	15	25	10	10	55	60	Did not sustain - boron/TFTA coating provides effective protection
20		–	–	100	–	–	25	Boron + TFTA	15	15	–	30	55	60	Did not sustain
21		–	40	60	–	–	25	Boron + TFTA	15	15	–	30	55	60	Did not sustain - boron/AP is extremely reactive particle - coating was adequate to prevent sustaining
22		–	–	100	–	–	50	None	0	20	–	–	80	50	Did not sustain - larger particle AP evaluated without coatings
23		–	–	100	–	–	45	None	0	18	–	–	82	55	Did not sustain - larger particle AP evaluated without coatings
24	Pure matrix	–	–	–	–	–	–	–	–	10	–	45	45	100	Did not sustain - no pellets or particles
25	Chunks, broken wafers	65	32	–	3	–	15	–	–	12	–	35	53	15	Did not sustain
26		58	39	–	3	–	35	–	–	7	–	40	53	35	Did not sustain
27		53	44	–	3	–	35	–	–	4	–	46	50	35	Sustained - high AP loading
28		49	48	–	3	–	41	–	–	5	–	50	45	41	Sustained - high AP loading
29		65	32	–	3	–	30	–	–	7	–	40	53	70	Did not sustain - no boron in matrix
30		65	32	–	3	–	30	–	–	–	10	40	50	70	Sustained - boron in matrix causes 40% AP to sustain
31		65	32	–	3	–	30	–	–	5	5	40	50	70	Sustained - boron in matrix causes 40% AP to sustain
32		65	32	–	3	–	30	–	–	–	15	35	50	70	Sustained - boron in matrix causes 40% AP to sustain
33	Chunks and pellets	65	32	–	3	–	15	Boron TFTA	–	–	–	–	100	25	Did not sustain - included 60% AP pellets in attempt to get bimodal loading - not as effective as pellets alone
34	Chunks and pellets	65	32	–	3	–	15	Boron TFTA	–	–	10	–	90	25	Did not sustain - included 60% AP pellets in attempt to get bimodal loading - only 75% loading

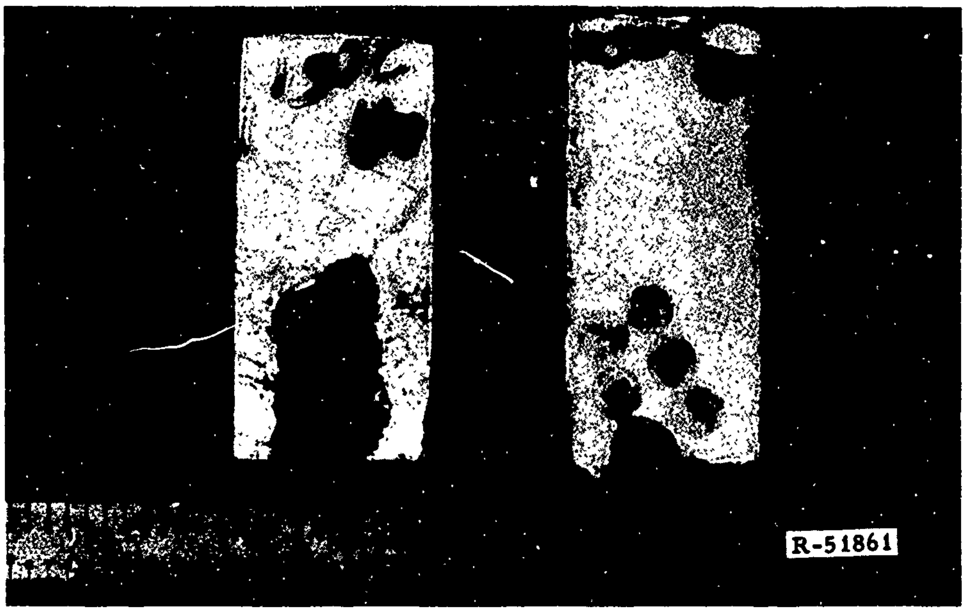

Figure 24. (U) Optical Bomb Samples

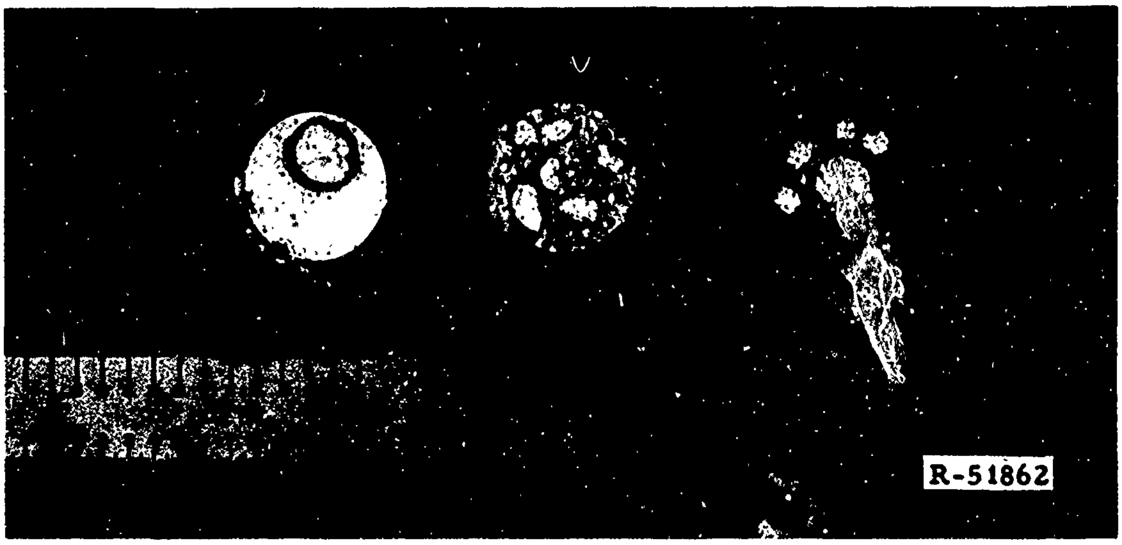

Figure 25. (U) Fuel Samples Containing Pellets and Particles

(C) To prevent interfacial burning of the pellets, coatings of various materials including fuel ingredients were evaluated. The pellets and particles with coatings were cast into fuel grains which included matrices of binder, and of mixes of one or more of the four ingredients. The results indicate that the AP particle size and boron content in the matrix is seen as a significant factor in the nonsustaining character of fuels. Matrices containing 36% AP, 24% boron, 40% binder sustained combustion and could not be inhibited by covering the AP particles with thin Kel-F coatings (tests 4, 5, and 6); whereas matrix formulations containing up to 40% large particle AP do not sustain if they do not contain boron. Boron apparently can be used in the matrix using the same ground rules that apply to homogeneous fuels tested in laboratory motors, that is, maximum AP loading of 40% and low (10%) boron content.

(C) Thin coatings of Kel-F and boron are sufficient to prevent interfacial burning of 100% AP pellets, but the intense reaction of AP/boron pellets requires increased coating thicknesses to prevent sustained combustion.

(C) The optical bomb studies indicate that formulations in practically any ratio up to 80% solids loading can be used to prepare high specific impulse, high density nonsustaining fuel combinations. Although large particle sizes and pellets involve certain undesirable processing procedures which are cumbersome to small quantity production of fuels, it is entirely conceivable that fuels containing large particles, compacted particles, or pellets can be produced in large production scale without significantly increasing propellant costs. Although propellants of this category have not been characterized at this time for use in full-scale motor tests of this program, they do have the potential for allowing high-performance gains not otherwise available.

4. Subscale Motor Test Program

(U) Candidate fuel systems were evaluated in two subscale motor sizes. A 3.5-in.-diameter motor, which is shown schematically in figure 26, was used to screen fuel samples from laboratory mixed batches involving only 1 or 2 lb of fuel per motor. The 5.0-in.-diameter motor, shown in figure 27, was used to characterize the regression-rate

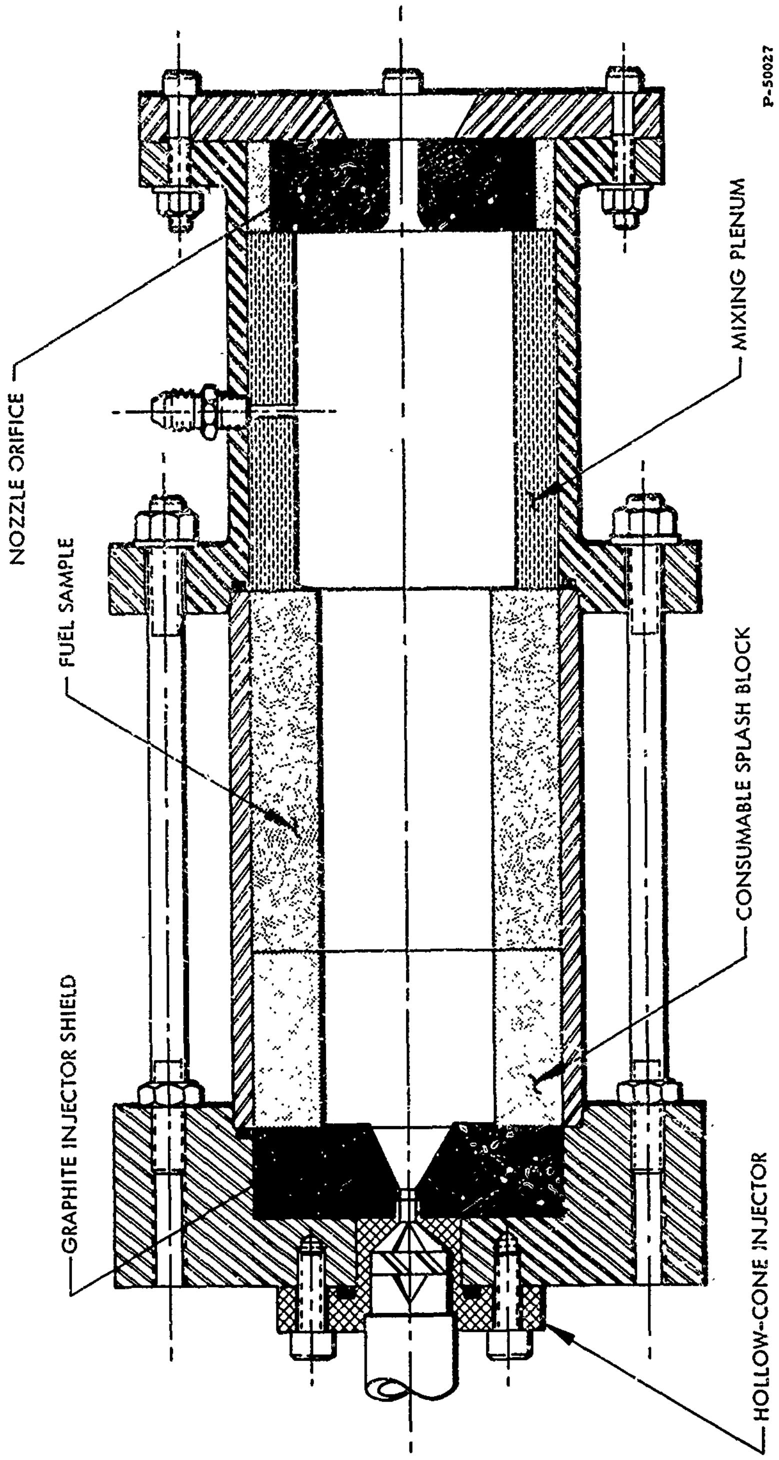

Figure 26. (U) 3.5-in.-Diameter Hybrid Motor

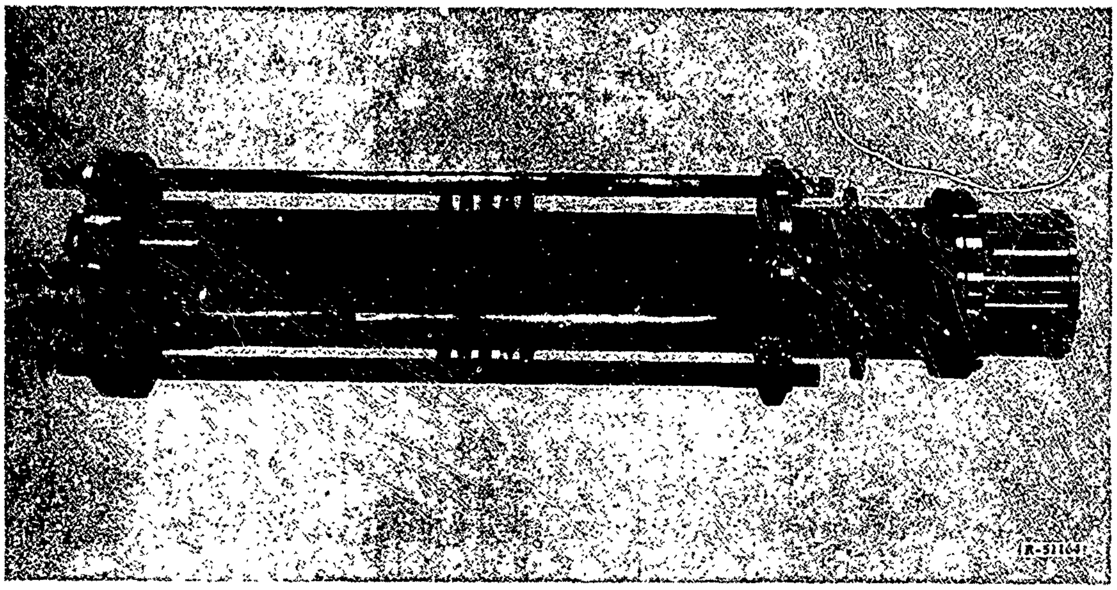

Figure 27. (U) 5.0-in.-Diameter Hybrid Motor

behavior of fuels which previously have been screened in the 3.5-in.-diameter motor, and was also used in evaluation of injectors and components. The 5.0-in.-diameter motor requires 10 to 20 lb of fuel.

5. 3.5-In. Motor Tests

(U) The 3.5-in. motor was used in 48 fuel development tests which were divided into five series. All test used the QX/DER binder which was subsequently replaced by the R-binder. These fuels also use small particle (175μ) AP which was subsequently replaced by 600μ to 800μ AP. Test of the R-binder fuels was continued in survey motor tests previously described and 5.0-in. motor tests described in subsequent sections.

(C) The initial 3.5-in.-diameter motor tests, series I (see table XII) were originally directed toward obtaining preliminary regression rate data for fuels containing TFTA, boron AP, and QX/DER binder, these fuels being slated for use in full-scale motor testing. However, the initial tests indicated

TABLE XII

(U) SUMMARY OF 3.5-in.-DIAMETER MOTOR TESTS

Test No.	Q-Binder %	AP %	Metal (Al or B) %	TFTA %	Type of Injector	Thrust	P_c psia	Oxidizer Flow Rate	Burning Time	Average Regression Rate	Comments
					Homogeneous Boron-Aluminum Fuels						
L40325	40	15	15B-5Al	25	Poppet	-	600	0.257	16	-	Sustained - Heavy char
L40326	40	15	10B-10Al	25	Poppet	-	535	0.258	15	-	Sustained - Char
L40327	40	15	5B-15Al	25	Poppet	38	570	0.258	18	-	Sustained - Char
L40328	40	15	20Al	25	Poppet	52	675	0.258	20	-	Sustained - Char
L40337	40	15	20B	25	WSF	58	670	0.257	4	-	
L40332	40	15	15B-5Al	25	WSF	60	750	0.257	16	0.0028	Sustained - Heavy char
L40333	40	15	10B-10Al	25	WSF	60	745	0.258	16	0.0264	Sustained - Char
L40334	40	15	5B-15Al	25	WSF	-	-	-	-	-	
L40335	40	15	20Al	25	WSF	61	745	0.257	16	0.0371	Sustained - Light char formed after firing
L40336	40	15	15B	30	WSF	-	-	-	2	-	
L40329	40	15	10B-5Al	30	WSF	55	640	0.258	~3	0.0273	Gas leak
L40330	40	15	5B-10Al	30	WSF	62	715	0.258	16	0.0416	Sustained - Thin char layer
L40331	40	15	15Al	30	WSF	66	710	0.257	16	0.0373	Sustained - No char formation
					High Ammonium Perchlorate Fuels						
L40338	30	40	15B	15	WSF	170	520	0.70	8	0.0922	Fuel completely consumed
L40339	30	40	15Al	15	WSF	150	450	0.697	5	0.130	Fuel completely consumed
					Pelletized High AP Fuels						
H15A33	17	46	17Al	20	WSF	-	700	0.297	7.35	-	Sustained 8.54% AP in matrix
H15A42	23.1	34.2	23Al	19.7	Wsf	-	450	0.302	3.58	-	Gas leak
H15A37	21.8	41.5	14.8B	21.9	WSF	-	550	0.295	7.30	-	Sustained - Hard dense char
H15A34	24.9	39	18.7B	17.4	WSF	-	600	0.297	7.37	-	Sustained - Hard dense char
H15A44	22.9	34.3	23B	19.8	WSF	-	-	0.302	1.5	-	Gas leak - Heavy char
H15A35	24.1	31.1	18.1B	26.7	WSF	-	580	0.296	6.15	-	Sustained - Char
H15A36	22.7	23.2	17B	37.1	WSF	-	650	0.295	7.32	-	Sustained with 400 psi purge
H15A30	25	15 TMETN	20B	40	WSF	-	800	0.297	1.31	-	

TABLE XII

SUMMARY OF 3.5-in.-DIAMETER MOTOR TESTS (Continued)

Test No.	Q-Binder %	AP %	Metal (Al or B) %	TFTA %	Type of Injector	Thrust	P_c psia	Oxidizer Flow Rate	Burning Time	Average Regression Rate	Comments
Homogeneous Aluminum Fuels											
H15A40	30	15	20Al	35	WSF	-	680	0.297	12.38	0.0413	Nonsustaining
H15A41	30	15	20Al	35	WSF	-	750	0.297	12.38	0.0428	Nonsustaining
H15A48	35	10	20Al	35	Poppet	-	500		12.85		Sustained
H15A49	40	5	30Al	35	Poppet	-					Sustained
H15A50	40	5	20Al	35	Poppet	-					Sustained
H15A45	35	0	20Al	45	WSF	-	533	0.617	9.95	0.0343	Nonsustaining
H15A46	35	0	20Al	45	WSF	-	600	0.617	8.96	0.0394	Nonsustaining
H15A47	35	0	20Al	45	WSF	-		0.619	~2.73	-	
H15A39	35	12.5	0	52.5	WSF	-	950	0.302	0.5	-	Failed O-ring
Homogeneous Boron Fuels											
H15A38	35	20	15B	30	WSF	-	605	0.295	1.76	-	Sustained
L40305	40	15	20B	25	Poppet	65	280	0.635	3.4	0.011	Sustained
L40307	40	13.04	20.87B	26.09	Poppet	-	200	-	0.1	0.012	Sustained
L40309	40	10.91	21.82B	27.27	Poppet	72	325	0.66	12.8	0.001	Sustained - Heavy char
L40311	45	7.86	20.95B	26.19	Poppet	62	320	0.66	12.9	0.0057	Sustained - Heavy char
L40318	45	7.86	20.95B	26.19	Poppet	76	440	0.65	17.25	0.0226	Sustained - Moderate char
L40304	40	15	15B	30	Poppet	90	400	0.62	12.6	0.0091	Sustained - Heavy char
L40306	40	13.04	15.66B	31.30	Poppet	75	380	0.71	12.8	0.0145	Sustained - Heavy char
L40308	40	10.91	16.36	32.73	Poppet	70	320	0.66	12.7	0.001	Sustained - Heavy char
L40314	40	10.91	16.36	32.73	Poppet	67	435	0.67	10.1	0.0142	Sustained - Heavy char
L40310	45	7.86	15.71	31.43	Poppet	62	320	0.66	12.9	0.001	Sustained - Heavy char
L40312	50	0	20	30	Poppet	82	220	1.275	13.95	0.0123	Nonsustaining - 0.2-in. char
L40315	50	0	20	30	Poppet	60	270	0.66	12.6	0.0114	Nonsustaining - Some gassing - char
L40317	46.89	0	22.60	30.51	Poppet	60	275	0.66	15.77	0.0112	Nonsustaining - Some gassing - 0.25-in. char
L40316	44.99	0	18.34	36.67	Poppet	65	295	0.66	12.75	0.0135	Nonsustaining - Some gassing - flaky char
H15A43	35	0	20	45	WSF	-	600	0.302	10.5	-	

that the fuel system sustained combustion with almost all formulations. The test series was therefore directed toward redefining the maximum AP loading for nonsustaining fuels. The AP loading was reduced in each subsequent pair of 3.5-in.-diameter motors to obtain the upper AP loading limit. However, each of the fuel blends sustained combustion down to a limit of approximately 7.5% AP loading. It was observed in each case that a char layer existed which at first was thought to be attributed to the sustaining character. However, the final motor tests of series I for which the fuels contained no AP, also demonstrated charring after shutdown, as shown in figure 28. The charring appeared to be related to the boron content of the fuel.

(C) Previous tests conducted on Contract AF 04(611)-8516 using aluminum instead of boron and others using the R-binder instead of the QX/DER binder had demonstrated satisfactory shutoff without charring. Therefore, a second test series (II) was initiated to determine the relationship between charring and using aluminum and mixtures of aluminum and boron (sustained combustion) as the metal additive.

(C) Ratios of boron and aluminum mixtures were varied while the total metal content and TFTA, AP, and QX/DER binder ratios were constant.

(C) The depth of char and the tendency to sustain combustion were found to vary in direct proportion to the boron content. Occasionally, even fuels containing aluminum and no boron sustained combustion, although the tendency was significantly reduced. Fuels containing aluminum but not boron produced contradictory results, in that the sustaining character of the fuel was independent of AP content. Fuels with 15% AP did not sustain combustion while fuels with no AP did sustain combustion.

(C) The discrepancy between these data and previous data using the R-binder suggested that the QX/DER binder along with the boron charring phenomena may contribute toward the tendency to sustain combustion. Subsequent laboratory studies discussed previously tended to substantiate this theory.

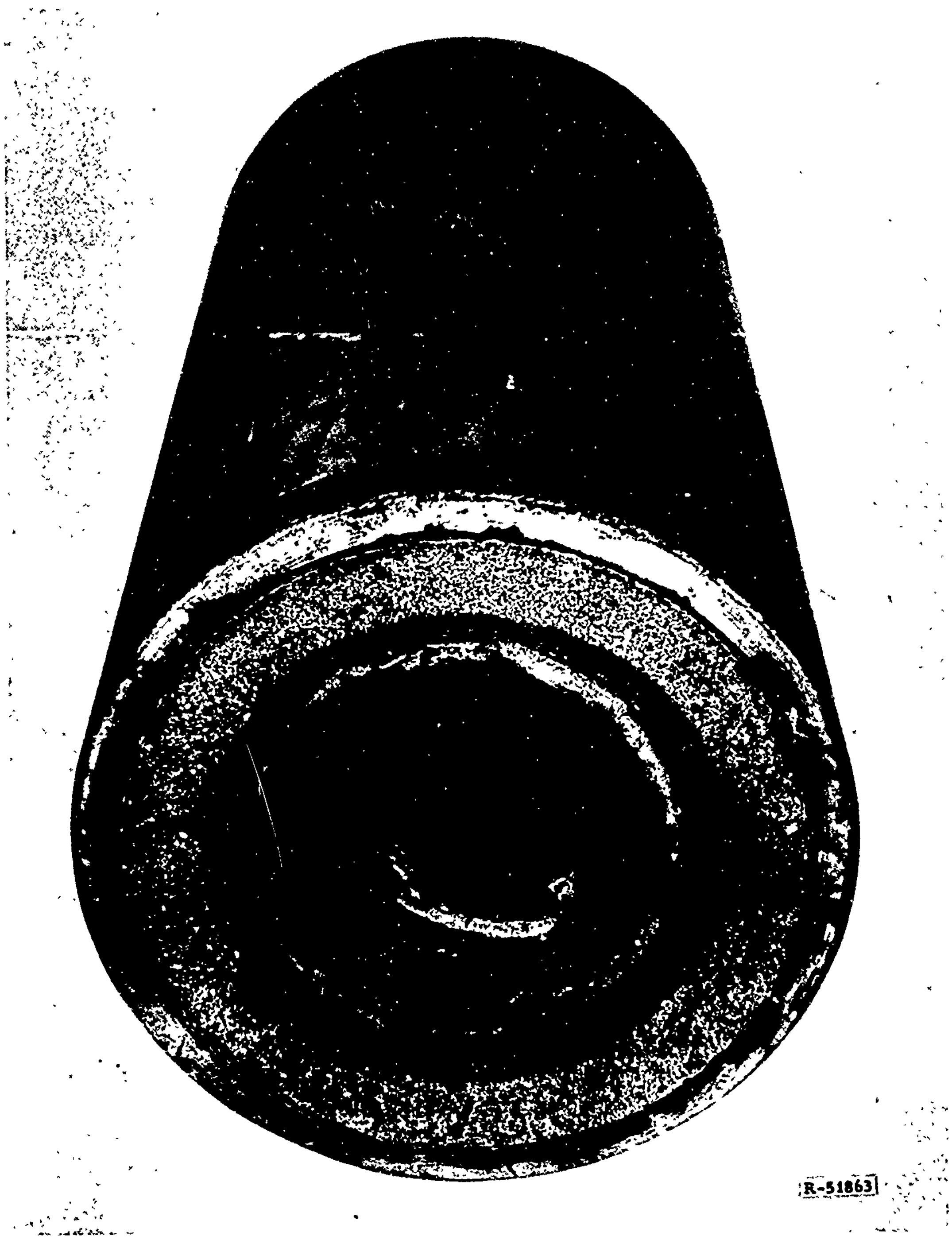

Figure 28. (U) Fuel Charring After Shutdown

(C) The higher AP loadings (15%) produced significantly higher regression rates, and it was theorized that the high regression rates would reduce heat transfer to the fuel grain and thereby reduce the tendency to sustain combustion. A third test series (III) was then conducted to determine whether augmented regression rates could reduce the charring and sustaining tendency. Two tests were conducted to determine if by augmenting the regression rate with high AP loading, the charring, which occurred during other tests, would be eliminated. The tests included one motor with boron and one with aluminum as the metal additive. Although the fuels sustained combustion as expected, no sintered boron char remained. The motor containing aluminum used as a reference system performed identically. Both fuel systems, incidentally, would make ideal fuels, with respect to performance and physical properties, for a hybrid propulsion system requiring thrust variation, but not on-off operation.

(U) It was concluded from these tests that the sustaining combustion problem was related to the use of the oxygen-containing QX/DER binder system. The laboratory studies previously discussed tended to substantiate this theory. However, the boron char, associated with high boron loading and low regression rates contribute to the problem. The use of the QX/DER binder system was discontinued in favor of the proven R-binder system as a result of these tests. However, subsequent test experience has shown that the use of relatively large quantities of graphite in the mixer assembly can produce the sustaining characteristics observed on these tests. Further testing should be conducted to verify the sustaining characteristics of the QX/DER binder before it is dismissed entirely.

(C) A fourth series of 3.5-in.-motor tests was conducted to evaluate pelletized fuel systems. Tests conducted on Contract AF 04(611)-8516 produced nonsustaining pelletized fuels when aluminum was used as the metal additive and had resulted in a sintered char and sustained combustion when boron was used. The fuel grains shown after test in figures 29 and 30 used AP pellets which were in contact with each other when cast. All other additives were included in the matrix. Since pelletizing removes approximately 50%

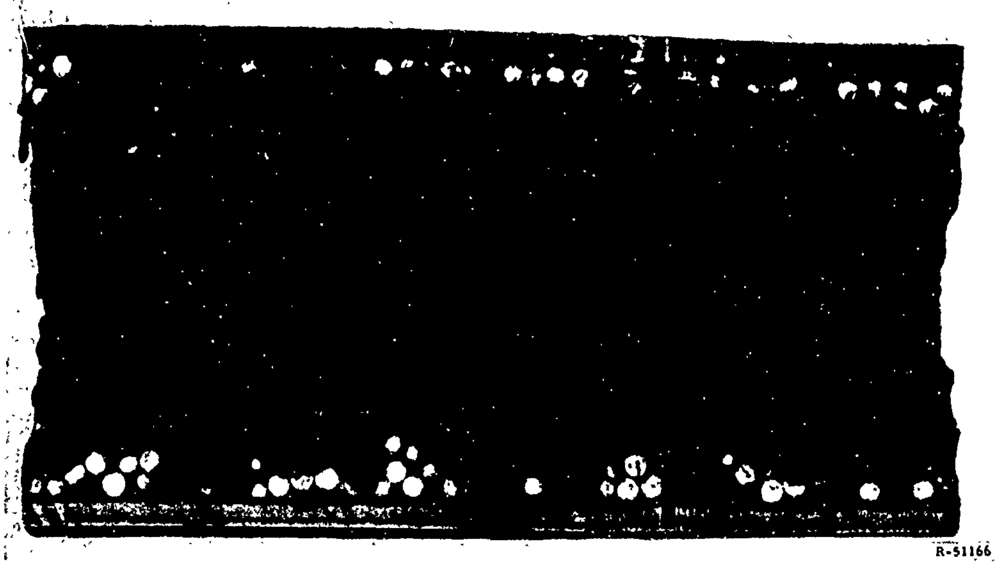

Figure 29. (U) 5.0-in. Fuel Grain Containing Boron and Pelletized AP, After Test

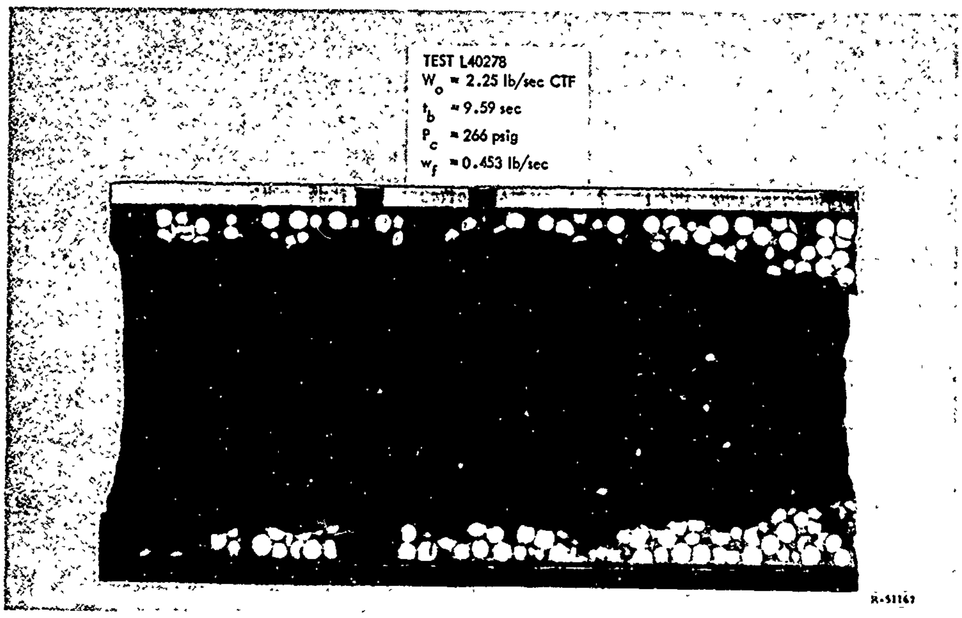

Figure 30. (U) 5.0-in. Fuel Grain Containing Aluminum and Pelletized AP, After Test

of the ingredients from the matrix, the ratios of the ingredients become doubled. Therefore, 20% boron becomes 40% of the matrix, and 40% boron without some means of promoting boron combustion results in the sintered structure and sustained combustion.

(C) Test series IV was therefore initiated to develop a pelletized fuel which did not sustain combustion. Although the tests conducted on Contract AF 04(611)-8516 indicated the feasibility of the tests resulted in nonsustaining fuels. The problem is a multifacet affair with simultaneous consideration of limitations placed on the pellet and on the matrix as having separate combustion characteristics while the overall formulation must deliver maximum performance.

(C) The conclusion reached from this and previous tests indicate that a highly loaded AP fuel system can be developed using aluminum rather than boron, but that simple pelletization of AP will not produce a satisfactory boron-containing fuel. The problem of formulating a boron-containing pelletized fuel was relegated to laboratory optical bomb studies previously discussed which indicated that sufficient pellet separation can be achieved by coating pellets with fuel constituents, thereby maintaining the most desirable formulation. However, further motor testing of pelletized fuels was limited to one 5.0-in. motor test which sustained combustion.

g. 5.0-in. Motor Test Program

(U) Sixty-one 5.0-in. motor tests were conducted on this contract with 36 involved in investigation of combustion characteristics of fuels discussed in the previous section. The motor configuration shown in figure 27 was used in five test series, the first two of which were component development tests described in the appendix of this report.

(U) Nine 5.0-in. motor tests were conducted in the development of the full-scale fuel grain. These tests are discussed in the following section.

2. FUEL GRAIN SHAPE DEVELOPMENT

(C) A hybrid fuel grain shape has been developed which will provide the required fuel delivery rate in a short L/D ratio motor. The 18-in. fuel grain shape shown in figure 32 uses six active fuel ports into which oxidizer is sprayed. Each active port has seven inactive "satellite" ports clustered about it which do not burn until the web between each inactive port and the active port is consumed. The successive burning of inactive ports results in an essentially constant fuel flow rate with the fuel now being used. The grain shape provides a cross-sectional loading fraction of 92% and a sliver fraction of 6.7%, both of which may be improved even further with some modification. The multiple port fuel grain configuration overcomes the design obstacles which are considered characteristic of hybrid rocket motors and which result from regression rates which are relatively low when compared to those of a solid rocket propellant.

(C) The fuel grain shape is calculated to deliver a fuel flow rate of 6 lb/sec at boost thrust oxidizer flow rate, 1.88 lb/sec/port, and 3 lb/sec at sustain thrust oxidizer flow rate, 0.38 lb/sec/port.

(U) The calculated fuel delivery rates and mixture ratios are shown in figures 32 and 33 for the anticipated maximum durations. These calculated data indicate that low fuel delivery rates will result in the first few seconds of operation. However, the experimental data obtained in four 5.0-in. motor tests and two full-scale motor tests would indicate that higher initial fuel flow rates are actually being delivered. Since the calculated low initial fuel flow rates do not actually occur, the high initial O/F ratios shown in figure 33 will also not occur. Since the O/F ratio curves are essentially constant after 5 sec of boost thrust operation and after 10 sec of sustain thrust operation, it can be concluded that essentially constant mixture ratio can be maintained for any duty cycle.

(U) The differences in operating mixture ratios between boost and sustain flow rates, illustrated in figure 33, were deliberately contrived to produce improved mixture ratios over the anticipated burning times. For instance, over short burning times (22 sec) at boost thrust, the average mixture ratio is 2.5. Sustain thrust operation is not anticipated until after some boost period. Therefore, the mixture ratio is optimized for the last half of the duty cycle at a value of approximately 2.5.

(U) Once the actual fuel flow rates are determined in full-scale motor tests, the oxidizer flow rates delivered by the primary and aft injectors can be adjusted to produce any mean operating mixture. The deviation in actual mixture ratio will be approximately equal to the deviations indicated by the curves of figure 33 after the first few seconds of operation.

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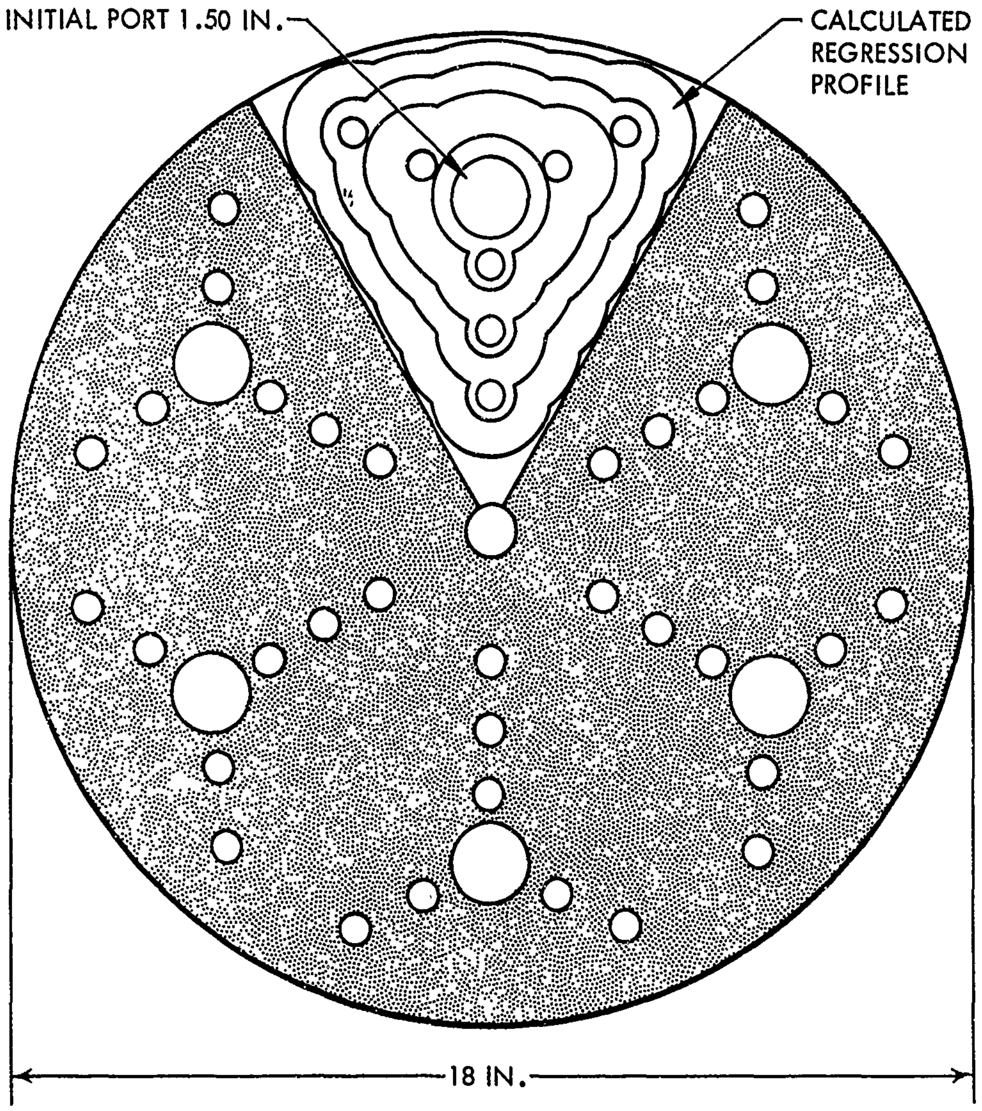


Figure 31. (U) Cross Section of 18-in. Fuel Grain

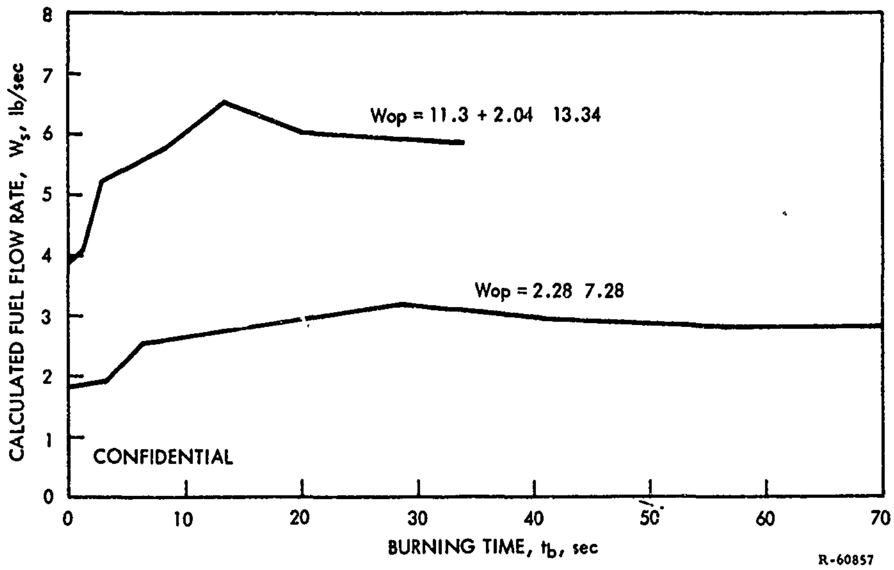


Figure 32. (U) Calculated Fuel Flow Rate

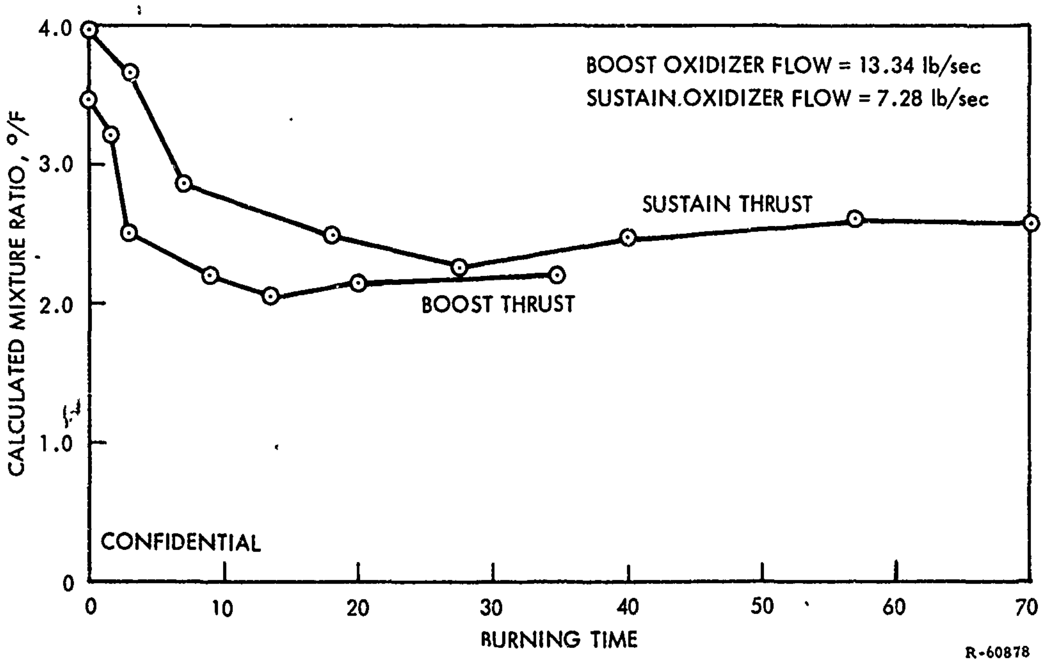


Figure 33. (U) Calculated Mixture Ratio

a. Design

(U) Hybrid fuel grain design is a matter of matching the fuel regression rate and fuel burning surface to deliver an essentially constant fuel flow rate as a function of burning time. The controlling factors in grain shape design are the relationships between fuel regression rate, oxidizer flow rate, fuel grain port area, and combustion chamber pressure.

(U) Hybrid fuel flow rate can be expressed:

$$\dot{w}_f = \rho_f L P_b \dot{r} , \qquad (1)$$

where:

$\dot{w}_f$ = fuel flow rate, lb/sec

ρ_f = fuel density, lb/in.^{3}

P_b = fuel burning perimeter, in.

L = fuel grain length, in.

$\dot{r}$ = regression rate, in./sec.

(U) The burning surface is a function of the diameter of the port which changes with time, and the regression rate is usually a function of oxidizer mass flux [(G_o) = (oxidizer flow rate ÷ fuel port gross section, lb/sec-in.^{2})] and possibly of chamber pressure.

(C) Extensive theoretical studies have been conducted on other programs in an attempt to theoretically predict the regression rates of hybrid fuels using convective and radiative heat transfer theory. However, it has been the experience of this program and that of Contract AF 04(611)-8516 that the theory is not yet sufficiently developed to handle fuel systems which incorporate ingredients which augment fuel regression rate such as ammonium perchlorate, THA, TAZ, and TFTA.

(U) Empirical relations have therefore been developed which express the regression rate as a function oxidizer mass flux and/or chamber pressure. Relations such as those below are then assumed and the constants and exponents are experimentally determined over the range of motor operating parameters.

(U) The assumed relations are:

$$\dot{r} = a G_o^{\,n} , \tag{2}$$

where regression rate is considered to be a function of oxidizer mass flux and:

$$\dot{r} = a G_o^{\,n} P_c^{\,m} , \tag{3}$$

where regression rate is considered to be a function of chamber pressure also. The mass flux, G_o, can be replaced in the equation by $\dot{w}_{ox}/A_p$ which is the ratio of primary oxidizer flow to fuel port area.

(U) The substitution of either equation 2 or 3 into equation 1 will result in a

$$\dot{w}_f = a \rho_f L (w_{ox})^n \frac{P_b}{(A_p)^n} ,$$

or

$$\dot{w}_f = a \rho_f L (w_{ox})^n \frac{P_b}{(A_p)^n} P_c^{\,m} .$$

(U) In either case it is evident that a constant fuel flow rate with burning time will result only when the parameter $P_b/(A_p)^n$ is constant. For example, if a cylindrical fuel port is used with a fuel which can be characterized with an exponent (n) equal to 0.5, a constant fuel flow rate with burning time is obtained.

(U) Since

$$P_b = \pi D$$

and

$$A_p = \frac{\pi D^2}{4} ,$$

then

$$\frac{P_b}{\left(A_p\right)^n} = \frac{\pi D}{\left(\frac{\pi D^2}{4}\right)^{0.5}} = 2\sqrt{\pi} = \text{constant} .$$

The fuel port diameter, D, being the only variable with burning time.

(U) Convective heat transfer theory predicts that the exponent (n) would be equal to approximately 0.8. With a circular port motor a regressive fuel flow rate would result, causing a constantly increasing mixture ratio O/F. However, experimental data with the type fuels under investigation on this contract in which additives augment regression rate indicate that lower exponents result. The lower exponent indicates a regression behavior which is less dependent on oxidizer flow and fuel port area.

(U) Constant fuel flow rates can be obtained by conventional solid motor design techniques if the exponent is zero (constant regression rate) and a neutral star grain configuration is used. If the exponent is 0.5, a circular port can be used, and if the exponent is between zero and 0.5, modified shapes can be used to produce constant fuel flow rate.

(U) The grain design used in the 18-in. full-scale motor and shown in figure 31 is designed to provide a constant fuel flow rate using equation 3 with a fuel having an exponent (n) equal to 0.4 and an exponent (m) equal to 0.1. The curves of figure 34 show the parameter $P_b/(A_p)^n$ for exponents of 0.4 and 0.6. The exponent n = 0.4 is used for calculations and it is the initial low value of the parameter that results in the low calculated fuel flow rate of figure 32. The curve of n = 0.6 is included to show the reversal in the trend. The low value of the parameter for n = 0.4, however, is compensated by the higher actual initial regression rate which has been observed in subscale and full-scale tests. Since the minor differences do exist between actual and predicted fuel flow rate, final modification of the fuel grain shape must await full-scale motor testing. Then accurate determination of fuel flow rate as a function of burning time can be made and the number and location of ports and slots can be adjusted to provide essentially constant fuel flow rate at both boost thrust and sustain oxidizer flow rates.

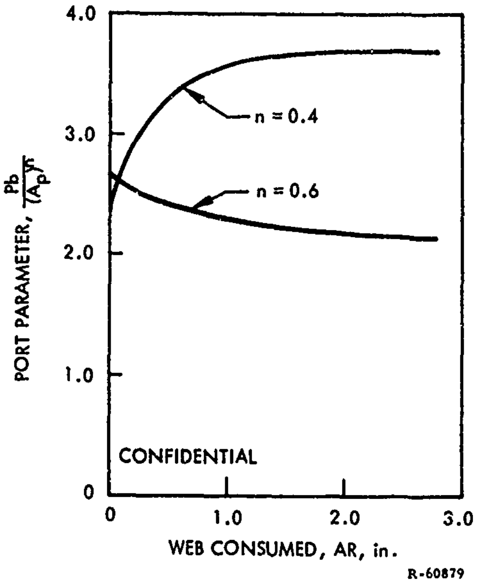


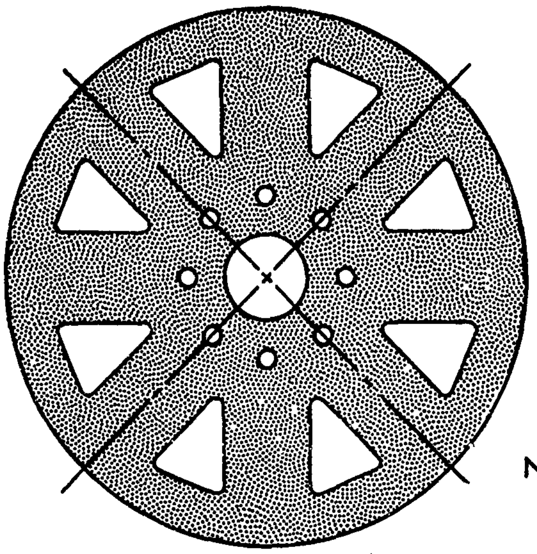
Figure 34. (U) Fuel Port Parameter vs Web Consumed

b. Development

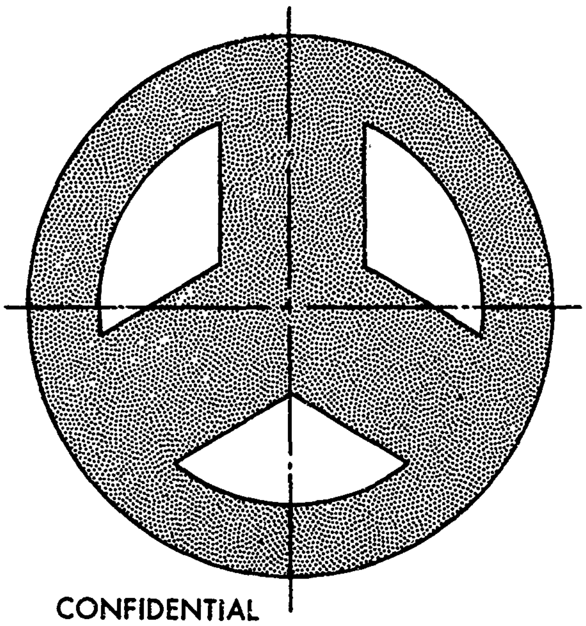
(U) The development of the fuel grain shape described above evolved from 12-in.-diameter motor studies conducted under Contract AF 04(611)-8516. These studies and subscale motor studies conducted under this contract are discussed in the following paragraphs to provide the background for the development of a fuel grain suitable for tactical missile propulsion systems.

(U) Hybrid fuel regression rates are characteristically low. Therefore, longer grain lengths are required for higher thrust single port motor designs. Typically, a single port fuel grain for a 5,000-lb thrust motor would be approximately 80 to 120 in. in length depending on the regression rate of the fuel and the optimum propellant mixture ratio O/F.

(C) Twelve-in. motor design studies conducted under Contract AF 04(611)-8516 resulted in the development and testing of two multiple-port fuel grain shapes which greatly reduced the required length of a 5,000-lb thrust motor. The fuel grain shapes are a three-port cartwheel design and a hubbed nine-port cartwheel grain shape, as shown in figure 35. The resultant reduction in motor L/D is shown in table XIII in which the benefit of multiple port fuel grain shapes is clearly indicated.



NINE PORT HUBBED-CARTWHEEL GRAIN DESIGN



CONFIDENTIAL

THREE-PORT CARTWHEEL GRAIN DESIGN

R-60881

Figure 35. (U) 12-in. Hybrid Motor Fuel Grain Shapes

TABLE XIII

(U) LENGTH-TO-DIAMETER RATIO
OF TYPICAL 5,000-lb THRUST HYBRID MOTORS

(Burning Time — 20 sec)

Grain Shape	Motor L/D	Motor Length in.	Motor Diameter in.
Cylindrical single port	7.8	78	10
Three-port cartwheel	2.9	36	12.5
Nine-port cartwheel	1.6	25	15.3

(C) Each of these fuel grains was successfully tested twice under this contract and demonstrated efficient and predictable fuel utilization. These grain shapes had cross-sectional loading fractions of 89%, 80%, and sliver fractions of 8.5% and 6.3%, respectively, as compared to the grain shape which was developed under this contract with a loading fraction of 92% and a sliver of 6.7%.

(U) A high loading fraction is desirable for maximum system performance, but loading fraction is limited by the smallest port size which is usable. In addition, extremely small port sizes increase the sliver fraction beyond practical limits and result in poor fuel utilization. The large sliver fractions result from the long radii arcs produced from burning large propellant web thicknesses.

(C) Based on the success of the four tests of multiple-port grain shapes tested under Contract AF 04(611)-8516, design studies were conducted during this program which incorporated the concept of using inactive ports in a multiple-port design to promote fuel regression in the direction of corners which normally would result in high fuel sliver volume. The study resulted in the grain shape now being used which permits an extremely high loading fraction and a sliver fraction which can be easily improved upon.

(C) In order to determine if slots of smaller cross-sectional area could be used rather than the cylindrical inactive ports, a series of four tests were conducted with 5.0-in. motors with the grain shape, as shown in figure 36. The tests show that the slots produce predictable regression behavior if one assumes a uniform regression rate over the burning perimeter. The results indicate that even further reduction in sliver fraction can be accomplished by using slots in the fuel grain corners and that a slight increase in the loading fraction can be obtained by substituting slots for the cylindrical inactive ports.

(C) Four more 5.0-in. motor tests (table XIV) were conducted using the selected fuel system (30% TFTA, 5% boron, 30% AP, and 35% R-binder) in a grain configuration similar to one major port of the full-scale motor. The fuel grains are shown before test (figure 37) and after test (figures 38 through 41). Two tests were conducted at the boost thrust oxidizer flow rate and chamber pressure (1,000 psi), and two were conducted at sustain-thrust oxidizer flow rate and chamber pressure (500 psi).

(C) The test results summarized in table XIV indicate that high regression rates are obtained initially in contrast to the analytically anticipated low rates.

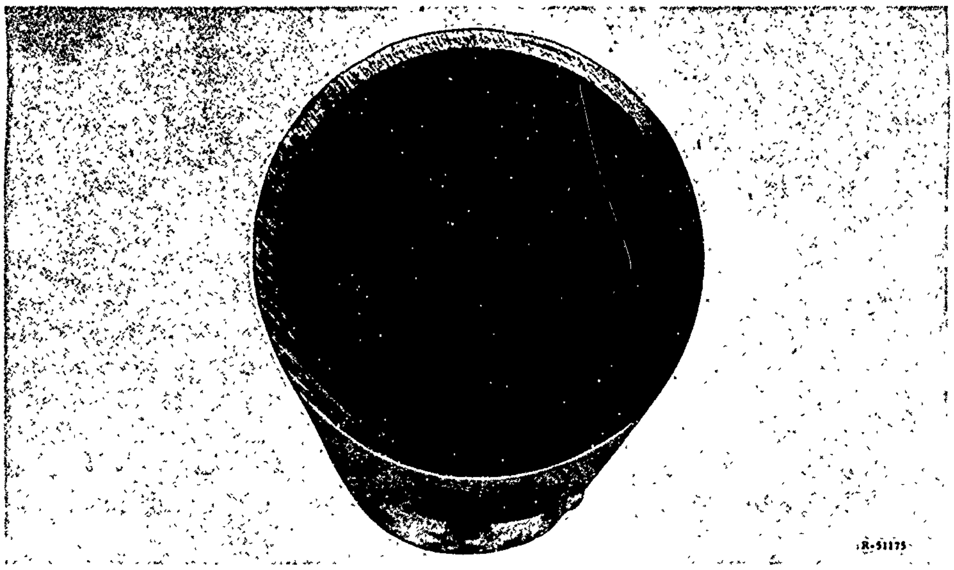
TABLE XIV

(U) SUMMARY OF 5.0-in. MOTOR TESTS CONDUCTED IN GRAIN DEVELOPMENT PROGRAM

Series V

Test No.	Thrust Level	Oxidizer Flow Rate lb/sec	Chamber Pressure psia	Duration sec	Average Regression Rate in./sec	Average Fuel Flow Rate lb/sec
9	Boost	1.88	1,050	9.0	0.098	0.59
10	Sustain	0.38	570	17.0	0.050	0.30
11	Sustain	0.38	590	9.8	0.066	0.39
12	Boost	1.88	1,050	4.5	0.14	0.97*

* Burning on outside diameter of fuel grain resulted in high indicated flow rate.



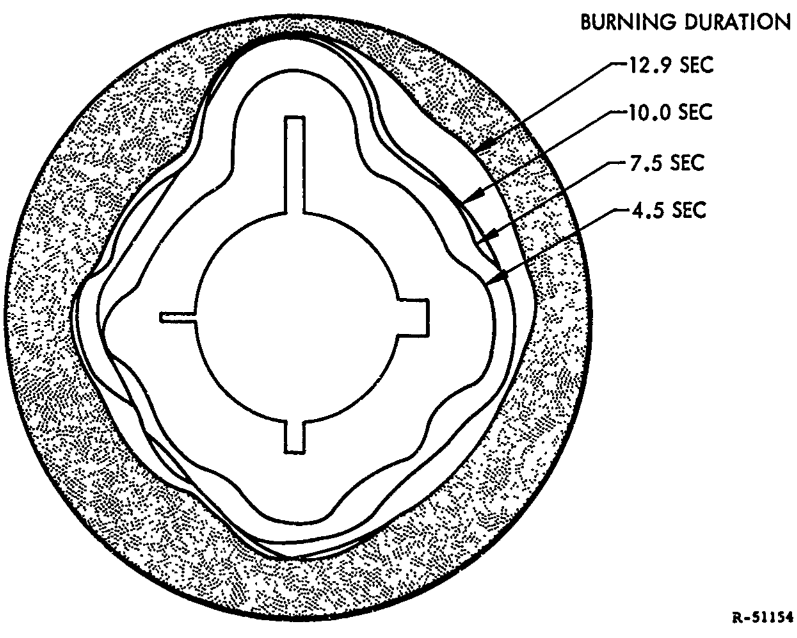


Figure 36. (U) Slotted 5.0-in. Fuel Grain

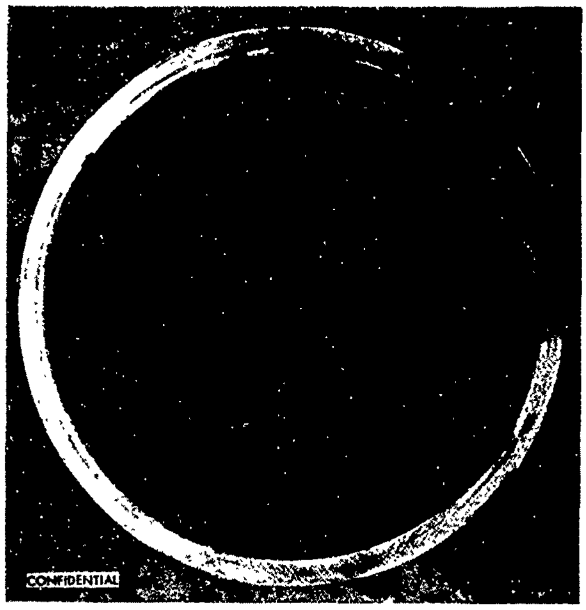


Figure 37. (U) 5.0-in. Subscale Fuel Grain Before Test

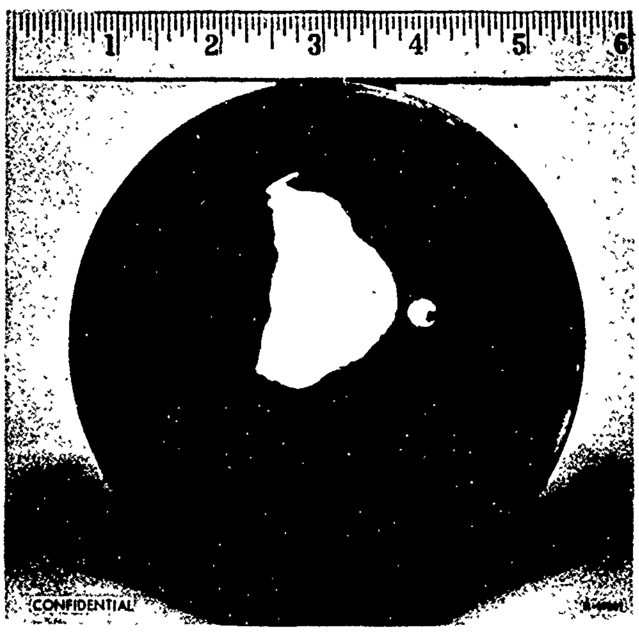


Figure 38. (U) 5.0-in. Subscale Fuel Grain After Test (H-17-A-9)

Figure 39. (U) 5.0-in. Subscale Fuel Grain After Test (H-17-A-10)

Figure 40. (U) 5.0-in. Subscale Fuel Grain After Test (H-17-A-11)

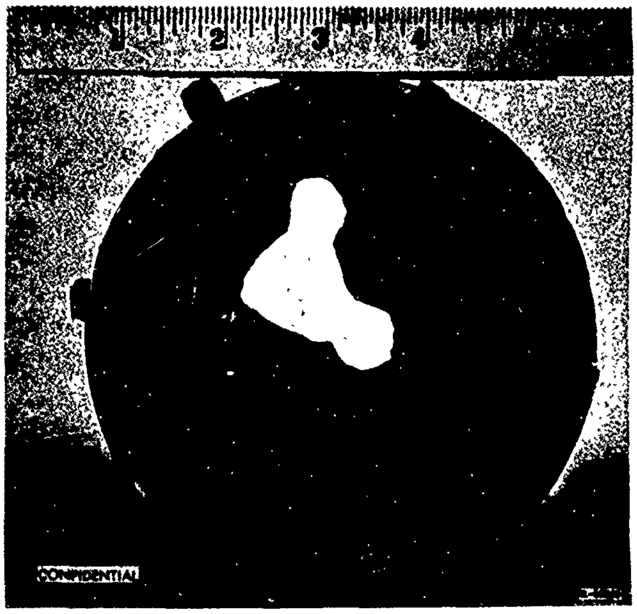


Figure 41. (U) 5. 0-in. Subscale Fuel Grain After Test (H-17-A-12)

(C) High initial flow rates have been observed in other tests conducted under Contract AF 04(611)-8516 in which slightly pressure sensitive fuels were being evaluated. Similarly high regression rates were observed with fuels containing THA and TAZ when fuel port diameters were less than 1. 5 in. in diameter. When port diameters exceed 1. 5 in. , either initially or as a result of burning during the initial few seconds of the test, the regression behavior conformed to an empirical relation similar to that being used on this program. The high initial regression rate is not undesirable, since it compensates for the low calculated initial fuel flow rates.

(C) The regression behavior of the fuel grains using the inactive or "satellite" ports also appears to be predictable from the photos of the four fuel grains in figures 38 through 41. Further evidence of predictable fuel regression behavior is available from the limited testing accomplished with the full-scale motor.

(C) The fuel of full-scale motor No. 003 was fired for 15 sec at sustain thrust level and burned essentially as predicted. The grain shown after test in figure 42 indicates that the fuel regression behavior was progressing as predicted. The fuel formulation used in this test was not that which was used to calculate the fuel flow rates shown previously in figure 32. However, the fuel contained similar basic ingredients and differed in regression rate by less than 15%. The differences are not sufficient to produce different overall regression behavior characteristics. The photo of the grain, shown in figure 43, indicates that uniform regression behaviors are obtainable from the fuel grain design. The results of the test of motor No. 007 conducted at boost thrust for 5.0 sec corroborate these indications. The fuel grain, shown in figures 44 and 45, employed the selected fuel system for which fuel regression behavior was observed in the 5.0-in. tests described above. Measurement of the fuel ports after the test indicate that the behavior is similar to that of the subscale tests, in other words, the actual regression behavior produces an initially higher fuel flow rate than the calculated fuel flow rates.

(U) Although the fuel grain design lacks complete verification in full-scale motors, it can be concluded from the tests already conducted that predictable regression behavior is obtainable for durations up to 9 sec at boost thrust level and 17 sec at sustain thrust.

(U) Past experience on Contract AF 04(611)-8516 indicates that regression behavior becomes more predictable and less sensitive to peculiarities of the grain shape as the fuel port opens. Therefore, no difficulties are forseen in obtaining the desired characteristics from the full-scale fuel grain in longer duration firings.

Figure 42. (U) Fuel Grain of Motor 003 After Test

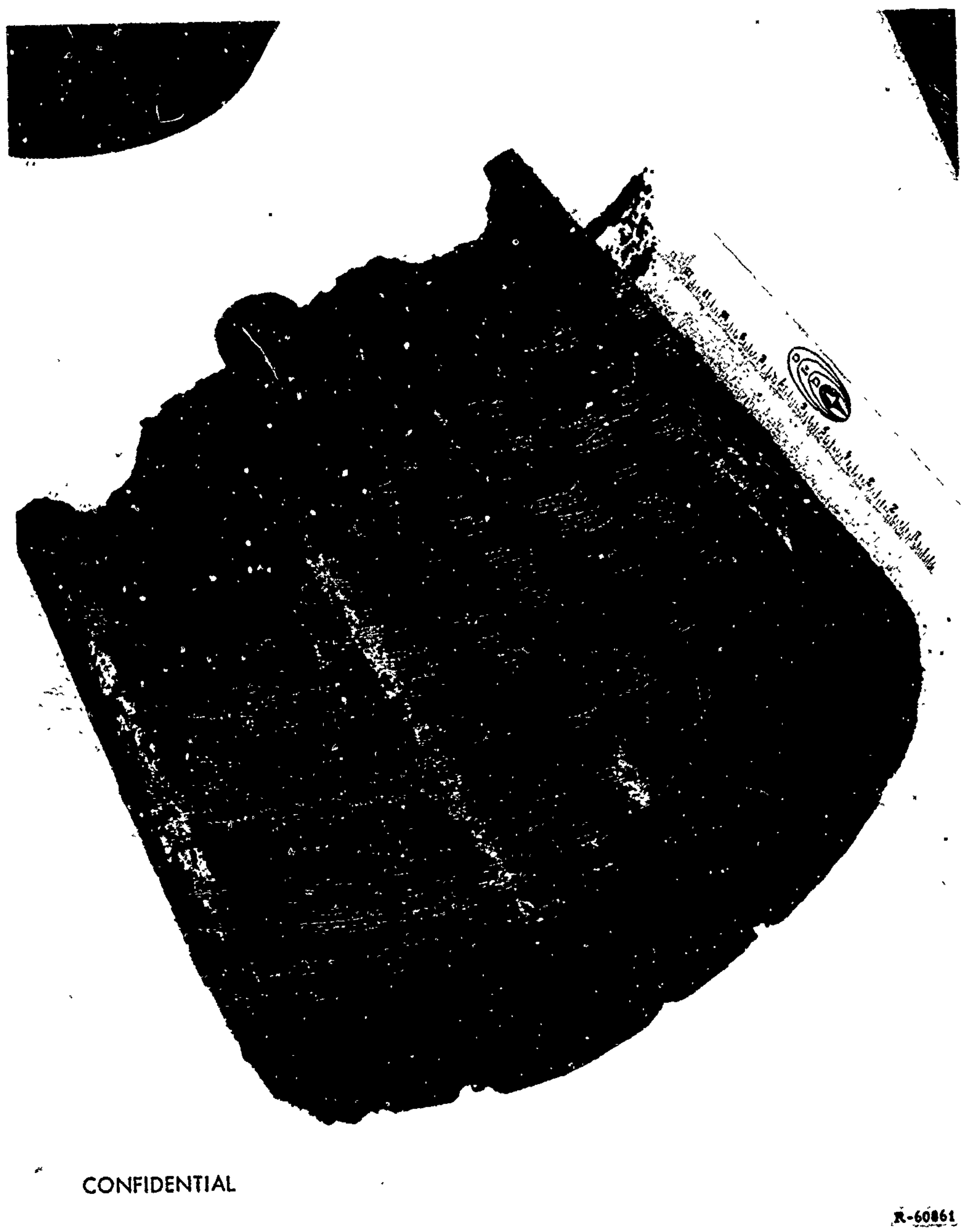


Figure 43. (U) Fuel Grain of Motor 003 Showing Uniform Regression Behavior

Figure 44. (U) Fuel Grain of Motor 007 After Test

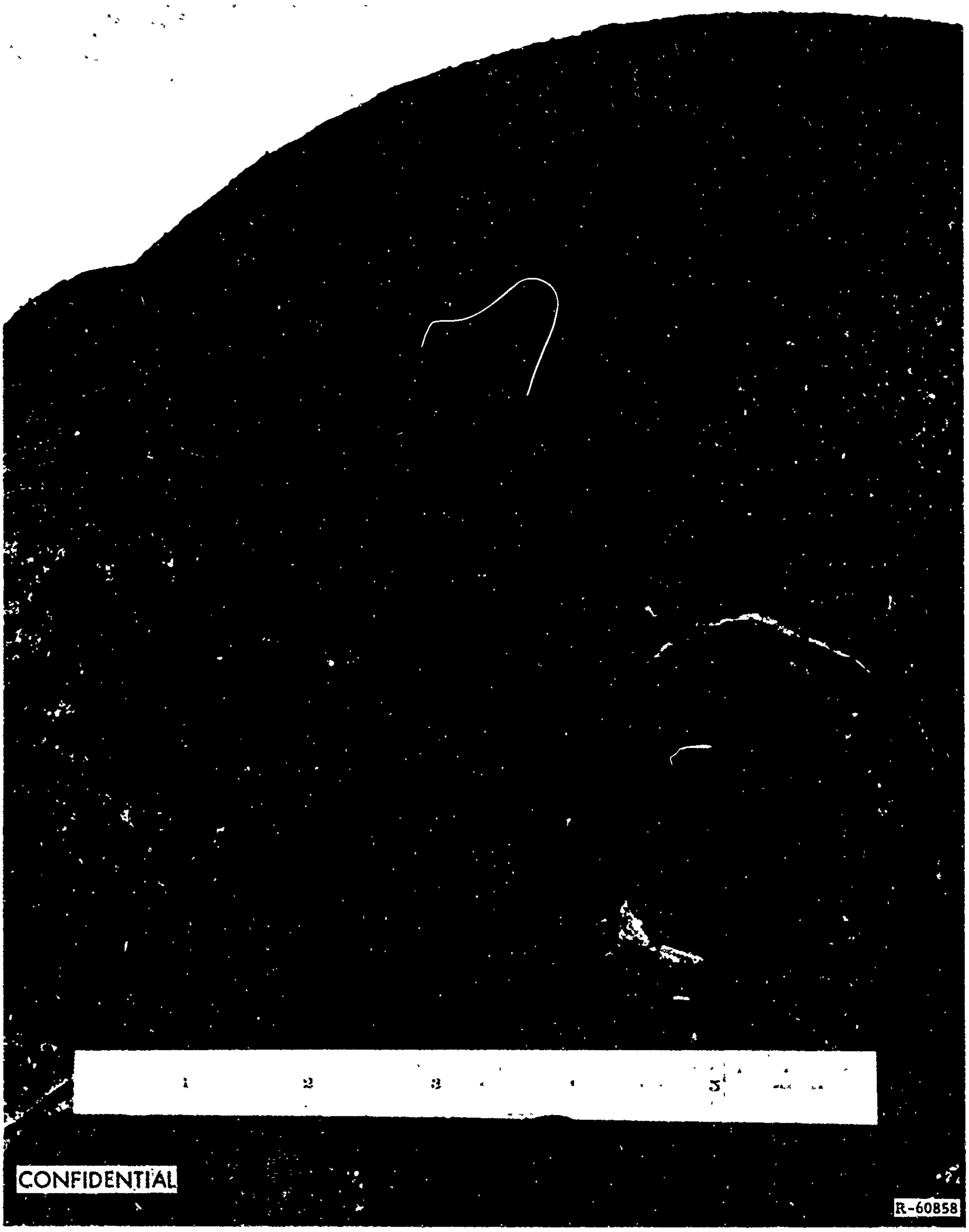


Figure 45. (U) Fuel Grain of Motor 007 After Test

SECTION V

THRUST CHAMBER DEVELOPMENT

(C) An 18-in.-diameter hybrid thrust chamber has been developed and fired in three full-scale motor tests with durations up to 15 sec. The TCA is designed for 1,000 psi chamber pressure during boost thrust and 500 psi during sustain thrust operation. The TCA when completely developed will be capable of delivering approximately 200,000 lb-sec of impulse at two thrust levels, as follows: 5,000 lb during boost, and 2,500 lb during sustain thrust operation. The TCA will be capable of delivering the impulse at boost thrust, sustain thrust or any combination of boost-coast-sustain-coast-sustain-type thrusting modes.

(U) Development testing has been conducted on all TCA components, including thrust control system, injectors, and motor case components. The results of these tests indicate that high energy hybrid propulsion systems may be feasible for use in advanced tactical missiles.

(C) The TCA (shown in figure 46) has been tested successfully for durations up to 15 sec. A thrust control system has been designed and fabricated which consists of a lightweight dual element solenoid valve, six dual flow primary injectors, and a fixed area aft injector. The injectors have been successfully tested in full-scale and subscale motors. The lightweight thrust control valve has been thoroughly checked in bench tests and now awaits testing in full-scale motor tests.

(C) A multiple (six) port fuel grain shape previously described has been designed and tested in full-scale and subscale tests for durations up to 17 sec. The fuel grain shape provides a cross-sectional loading of 92% while permitting almost complete utilization of fuel. When used with the fuels under development and the oxidizer flow control system, the fuel grain shape will produce an essentially constant mixture ratio with respect to burning time at both thrust levels.

(U) Limited development testing of the full-scale motors is completed. A test of the first version (designated Mark I) of the TCA indicated that modifications were required of the aft closure insulation. The closure was subsequently redesigned twice to obtain a suitable noncharring ablative aft closure. A nylon-phenolic aft closure assembly was developed for use on the Mark II motor which, in a full-scale test, was demonstrated to have to the desirable noncharring ablative characteristics.

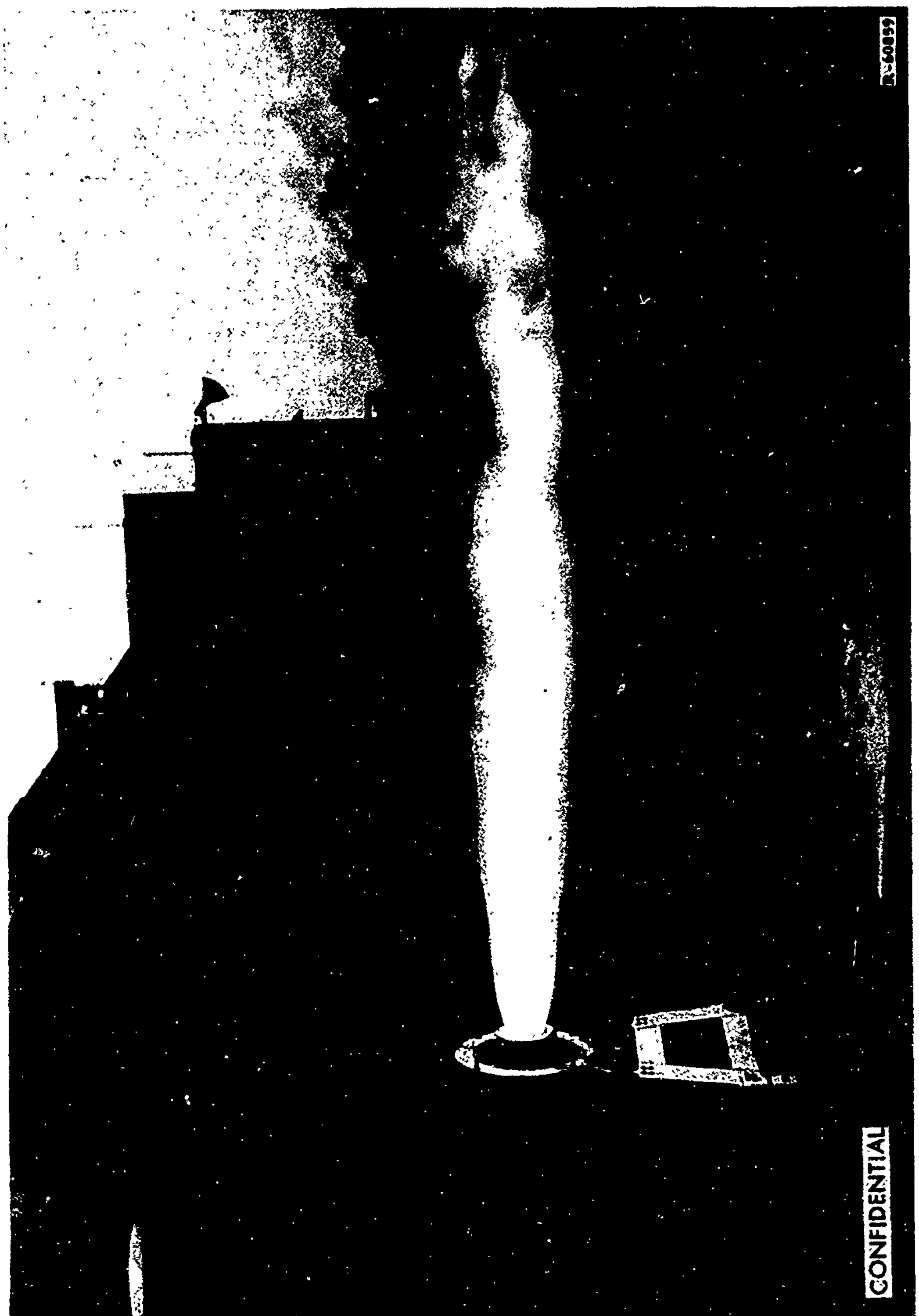


Figure 46. (U) Thrust Chamber Assembly During Test

1. THRUST CONTROL SYSTEM

(C) A simple thrust control system has been devised which, with one dual-element solenoid valve, can provide dual thrust operation as well as on-off control. The system shown schematically in figure 47 includes the dual element valve, six dual-manifold injectors, and a single fixed-area aft injector.

(C) During sustain thrust operation, oxidizer is supplied to the motor by the sustain thrust valve element while both valve elements supply oxidizer during boost thrust operation. Oxidizer is supplied to the dual element valve through a single feed line at a pressure of 1, 100 psi.

(U) Since boost thrust operating chamber pressure is 1, 000 psi and sustain thrust operating pressure is 500 psi, system pressure differentials of 100 psi at boost thrust and 600 psi at sustain thrust are available to control oxidizer flow through the injectors. All of the injectors are of the fixed-area orifice type. Therefore, as a result of changes in operating chamber pressure, the flow rates in the aft injector and sustain ports of the primary injector will change in the ratio of $(600/100)^{\frac{1}{2}}$, or 2.45, as thrust changes are made from 5, 000 to 2, 500 lb. This resultant increase in flow rate at lower thrust levels is easily accommodated by the nonlinear relationship between fuel and oxidizer flow rates.

(U) The distribution of oxidizer between primary and aft injectors at the boost and sustain thrust levels is a function of the sensitivity of fuel delivery rate to primary oxidizer flow rates and combustion chamber pressure. Experience with fuel of the type being evaluated has shown that it can be characterized reasonably well within the operating limits by an empirical regression rate equation of the form:

$$\dot{r} = a P_c^m G_o^n \quad ,$$

where

the operating limits are: P_c less than 1, 000 psi
G_o between 0.01 and 2.0 lb/sec-in.^{2}

and

$\dot{r}$ = regression rate, in. /sec

a = proportionality constant

P_c = combustion chamber pressure, psi

G_o = oxidizer mass flux (lb/sec-in.^{2}) = w_{op}/A_p

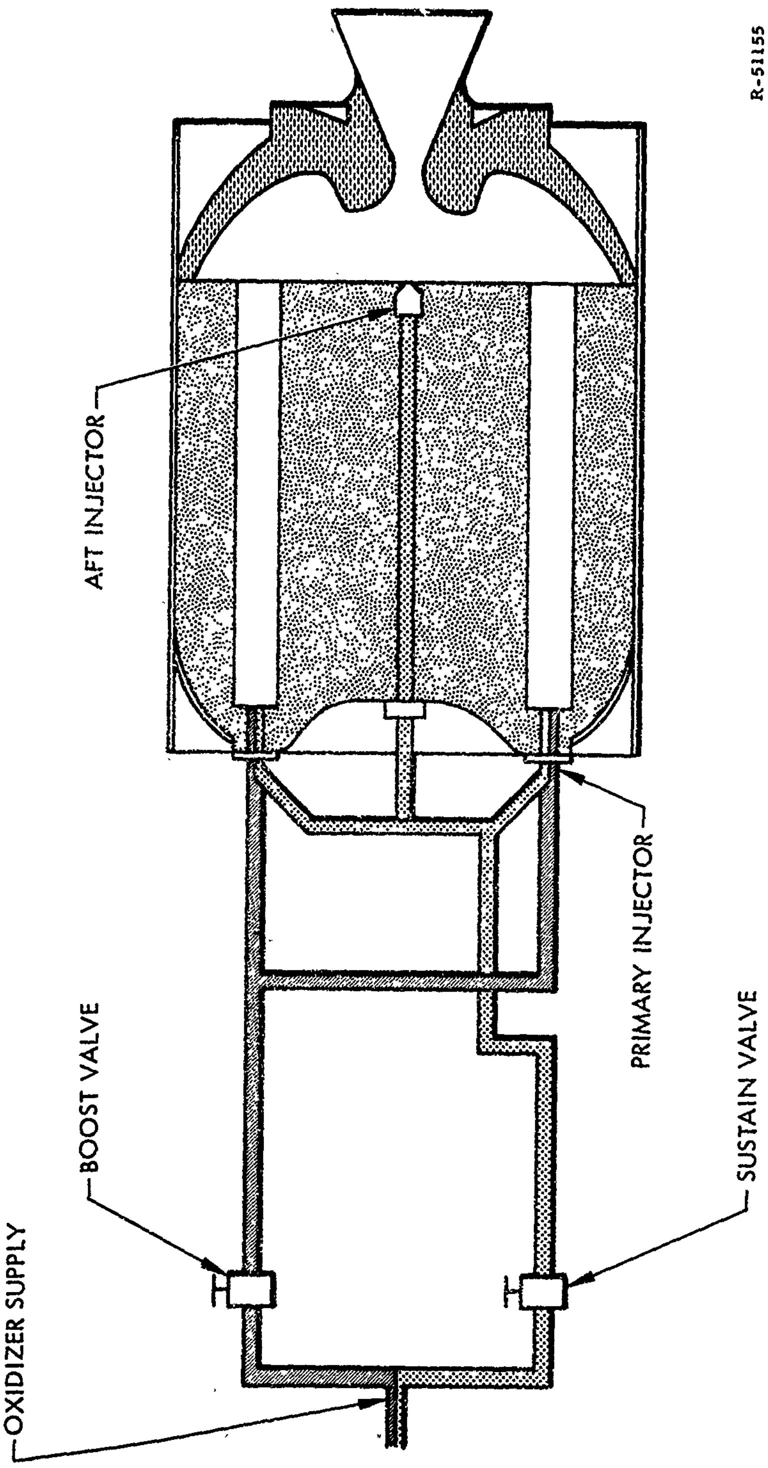


Figure 47. (U) Thrust Control System

w_{op} = primary oxidizer flow rate, lb/sec

A_p = fuel grain port area, in.^{2}

m = pressure exponent

n = oxidizer mass flux exponent,

with the exception that for very small fuel port diameters, higher than predicted regression rates occur. Experience with the fuel being investigated on this contract indicates that the value of the exponent, n, in the above equation is approximately 0.4 and m is approximately 0.1. Therefore, the ratio of boost-thrust primary oxidizer flow rate to sustain thrust primary flow rate required is 5:1 in order to achieve a boost to sustain thrust ratio of 2:1 with a constant mixture ratio.

(U) Since the relationship between the fuel flow rate and primary oxidizer flow rate is nonlinear, supplemental aft injection of oxidizer is needed in order to maintain a constant mixture ratio. However, by adjusting the aft flow rate at full thrust, the ratio of boost thrust to sustain thrust aft oxidizer flow rate can be adjusted over a very wide range.

(U) Because of the minor pressure sensitive regression of the fuel used, the latitude of choice of aft oxidizer flow ratios is not easily illustrated. If for example a system is used having no pressure sensitive regression behavior and an oxidizer mass flux exponent of 0.5, the latitude of choice given the designer can be clearly illustrated. Figure 48 shows the primary and aft oxidizer flow rates required of a typical 5,000-lb thrust hybrid motor as it is throttled over a continuous spectrum of thrust levels. Note that while the primary oxidizer flow rate is a linear logarithmic function, the aft flow rate requirement is generally inverse in going from 2,500-lb thrust to 5,000-lb thrust. Therefore, by judicious selection, the ratio of aft oxidizer flow rate at sustain thrust to that at boost thrust can be tailored to fit the ratio (2.45) provided by the system pressure differential change.

(U) A similar change in flow rate results in the sustain thrust orifices of the primary injector as the chamber pressure varies with thrust, but this can be accommodated by the oxidizer flow through the boost thrust valve.

(C) Parametric studies have been completed which determine the oxidizer flow distribution for typical combinations of fuel system pressure exponents and oxidizer mass flux regression rate exponents. Figure 49 gives the results of this study in oxidizer flow rates required for fuels of various characteristics. Table XV gives the oxidizer distribution for only one case which anticipates the exponents m and n to be 0.1 and 0.4, respectively. Although the final flow distribution was modified when

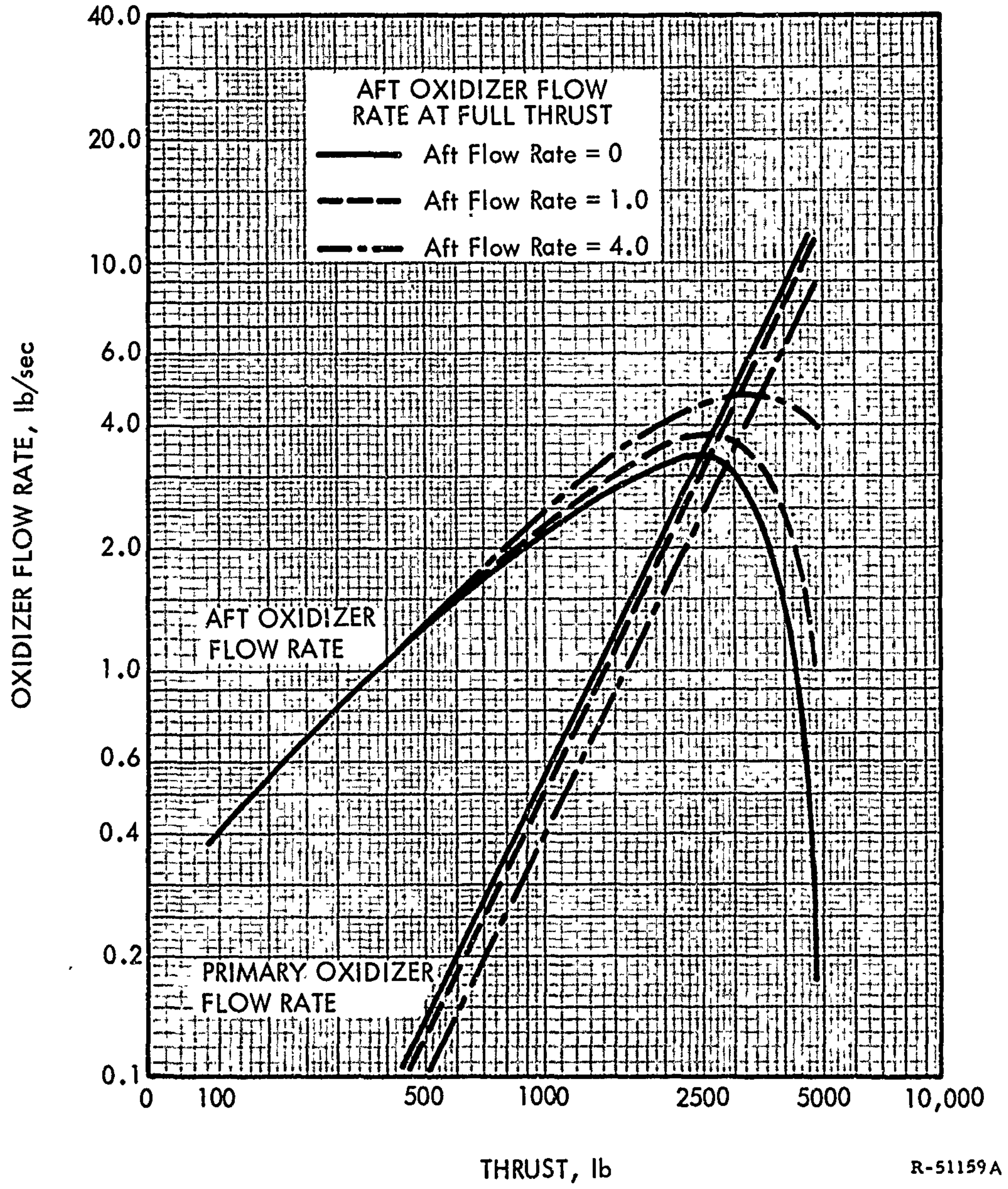


Figure 48. (U) Oxidizer-Flow Schedule for Throttled Operation

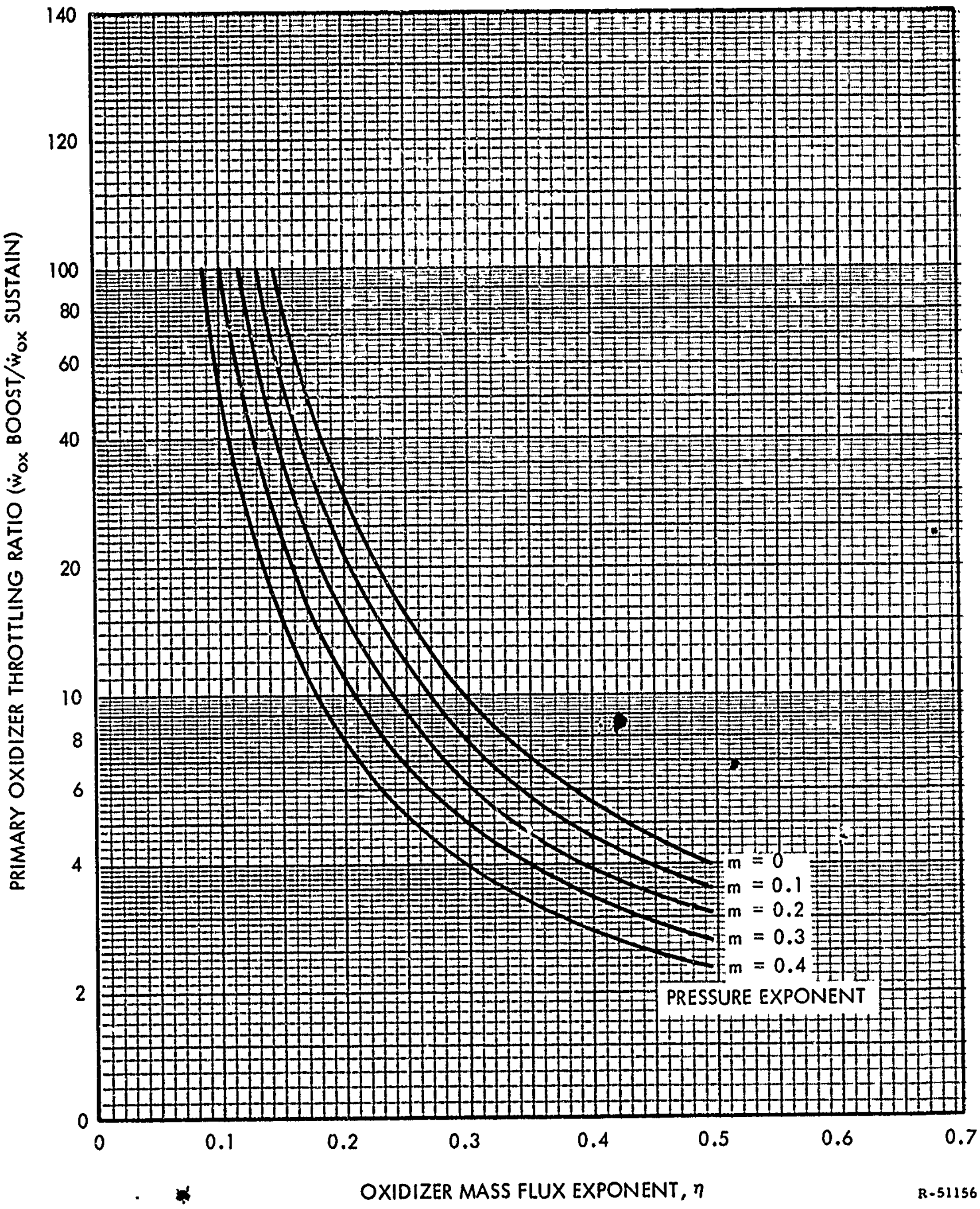


Figure 49. (U) Primary Oxidizer-Throttling Ratio Required for 2:1 Pressure-Throttling Ratio

characterization of the selected fuel system was completed, the flow rates given below are considered to be representative of the final configuration oxidizer flow-rate requirements, using ClF_5. (C)

TABLE XV

(U) OXIDIZER FLOW DISTRIBUTION

m = 0.1, n = 0.4, mixture ratio = 2.5 (O/F)

Injector	Boost Thrust lb/sec	Sustain Thrust lb/sec
Primary		
Boost orifice	10.4	0
Sustain orifice	0.99	2.42
Aft	1.68	4.12
Total	13.07	6.54

(U) Actual oxidizer flow rates used in full-scale motor tests using ClF_3 were established after subscale motor tests were conducted with the selected fuel. Slightly modified regression behavior resulted from minor differences in physical properties of the fuel. Therefore, slight modifications in oxidizer flow were required.

(U) Experience gained on this and on previous hybrid motor development contracts indicates that with the fuels being investigated and the thrust control system discussed here, dual thrust operation can be achieved while maintaining essentially constant mixture ratio at both thrust levels.

a. Control Valve Development

(U) To meet the operating requirements of dual thrust and random on-off duty cycles, a dual element thrust control valve, shown in figure 50, has been developed which, when used in the selected thrust control system, will provide both on-off and dual thrust operation from only two 28 v electrical signals.

(U) This valve, which is shown schematically in figure 51, is predominantly aluminum and consists of a common feed line, two pilot solenoids, and two main poppet valves which control

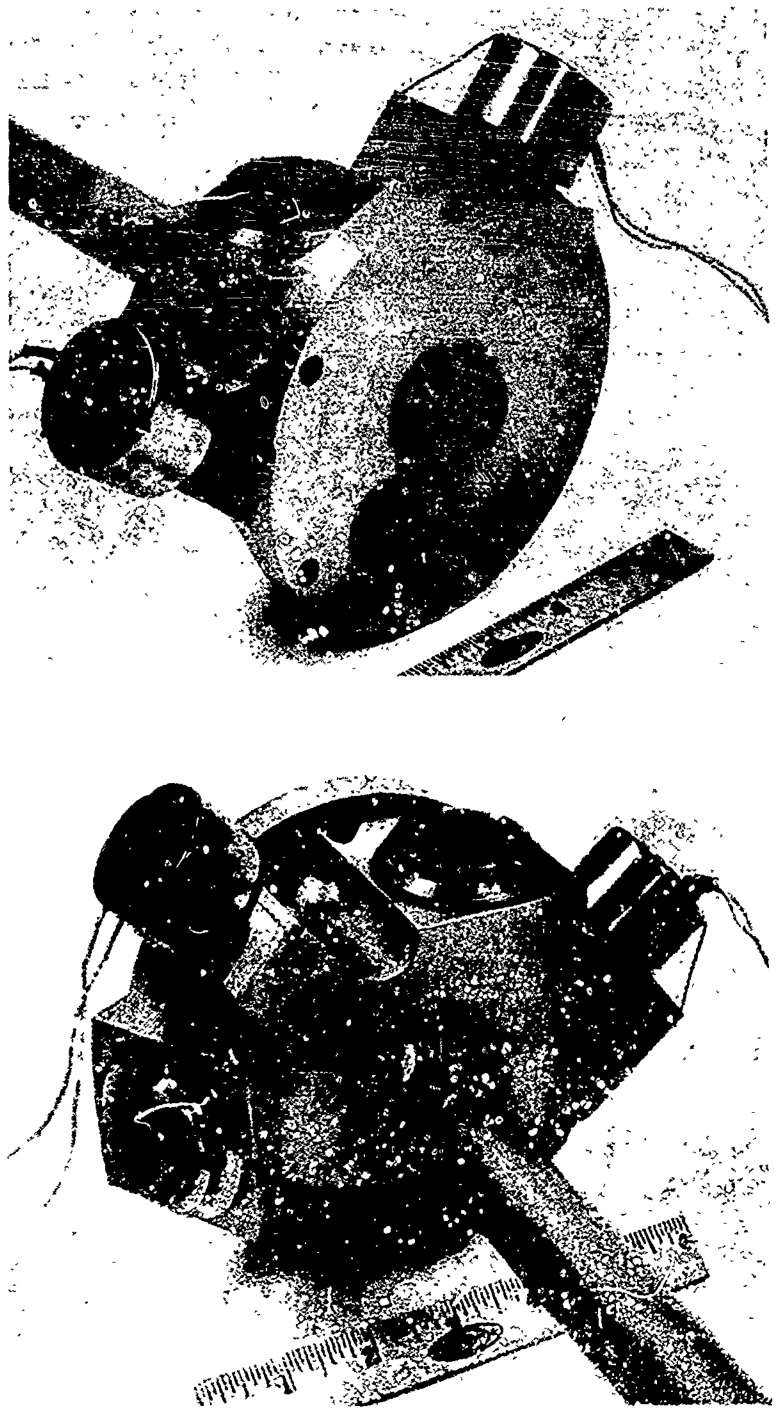


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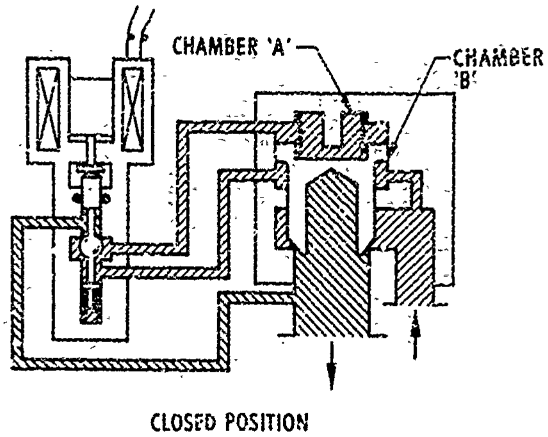
Figure 50. (U) Dual-Element Thrust Control Valve



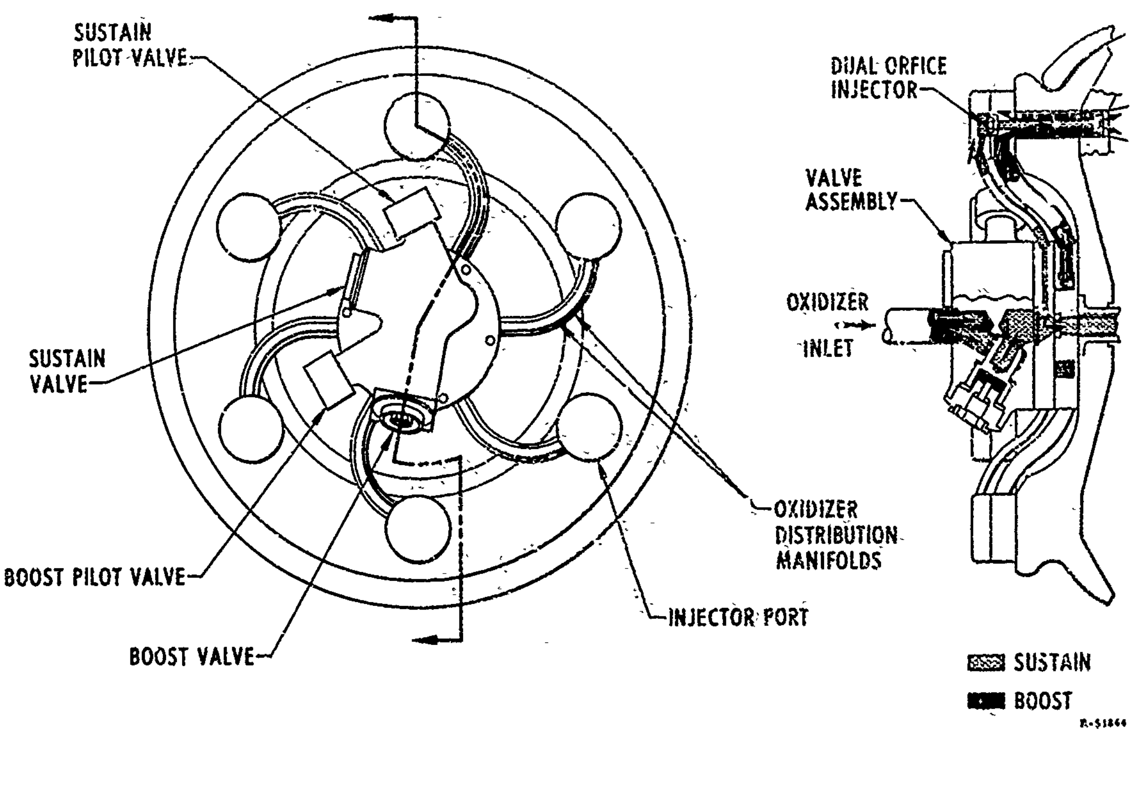


Figure 51. (U) Dual-Element Thrust Control Valve Schematic

oxidizer flow through two discharge manifolds, a boost thrust oxidizer manifold, and a sustain thrust oxidizer manifold.

(U) The valve mounts directly to the forward closure of the Mark II full-scale motor, thus providing a short overall length TCA. It is activated by application of a 28-vdc signal (0.9 amp) to the solenoid which causes the solenoid armature to push the pilot poppet to the opposite seat. Chamber A (see figure 51) is then vented to the valve discharge. The feed system pressure applied to chamber B causes a force unbalance on the poppet, thereby opening the main poppet. Removal of the electrical source causes the pilot poppet to return to the closed position. The feed system pressure is applied again to chamber A, causing the main poppet to close.

(U) The valve weighs only 5 lb and was designed to be amenable with low-cost mass production. No seals are used on the main poppet, and the valve seat is machined into the aluminum valve body. With proper handling and avoidance of foreign particles, this seat should have a service life of 50 cycles minimum and can be refurbished by subsequent lapping. Each pilot-poppet solenoid is removable without otherwise disturbing the valve. Each contains one dynamic seal which permits the use of small low-current solenoids and avoids the necessity of expensive bellows sealed poppets, as normally required for use with fluorinated oxidizers.

(U) The pilot poppet seal is a spring-loaded teflon packing that sells under a variety of trade names. Although teflon is not considered to be compatible with fluorinated oxidizers, it has been used with consistently satisfactory results in situations where the seal operates in a limited duty cycle and is removed from high-velocity oxidizer flow.

(U) Cycling tests conducted by the manufacturer indicate that the valve operates with response times of approximately 100 msec, and at pressures up to 1,500 psi.

(U) Water flow calibration tests, hydrostatic tests, and operational tests have been made with the valve, and the valve is now ready for installation and testing on full-scale motors.

b. Injector Development

(C) A dual manifold poppet injector has been designed, fabricated, and successfully tested for use with the selected thrust control system in delivering oxidizer throughout a dual thrust on-off duty cycle. The primary oxidizer injector shown in figure 53 delivers oxidizer at two flow rates and shuts off the oxidizer flow at the injector when flow is terminated upstream. The injector consists of an injector body and a spring-loaded poppet, as shown schematically in figure 53. The poppet contains a flow passage and fixed orifices which control oxidizer during sustain thrust operation. The injector body contains an annular flow passage and orifice which controls additional oxidizer flow used during boost thrust operation.

(C) The spring-loaded poppet is designed to open under oxidizer pressure from the sustain thrust valve manifold. The travel of the poppet is limited in travel by an adjustable nut, which merely prevents poppet oscillation. The external surface, on which the poppet seats, serves to direct the oxidizer flow axially into the motor. The injector spray pattern at boost and sustain flow rates is shown in figures 54 and 55 as the injector is undergoing calibration.

(C) Since the poppet is operated by oxidizer pressure, termination of flow upstream will cause it to close, thereby preventing backflow and possible contamination of the feed system with fuel-rich vapors. Contamination of the oxidizer feed system by residual fuel vapors could, on restarting, cause a reaction between contaminants and oxidizers, resulting in damage to the injectors.

(U) The dual manifold injector has been successfully tested in four 5.0-in. subscale motor tests in which full-scale motor fuel-grain-port configuration was accurately simulated. Two tests were conducted at sustain thrust oxidizer flow rates (0.38 lb/sec) and chamber pressure (500 psi) for up to 17-sec duration. Two tests were conducted at boost thrust oxidizer flow rate (1.88 lb/sec) and chamber pressure (1,000 psi) for up to 9.0-sec duration. The injector shown in figures 56 and 57, with condensed fuel deposits on the face, is typical of injectors after motor shutdown. Injectors in similar condition have been restarted without injector damage. The uncontaminated internal surface of the poppet illustrates the ability of the poppet

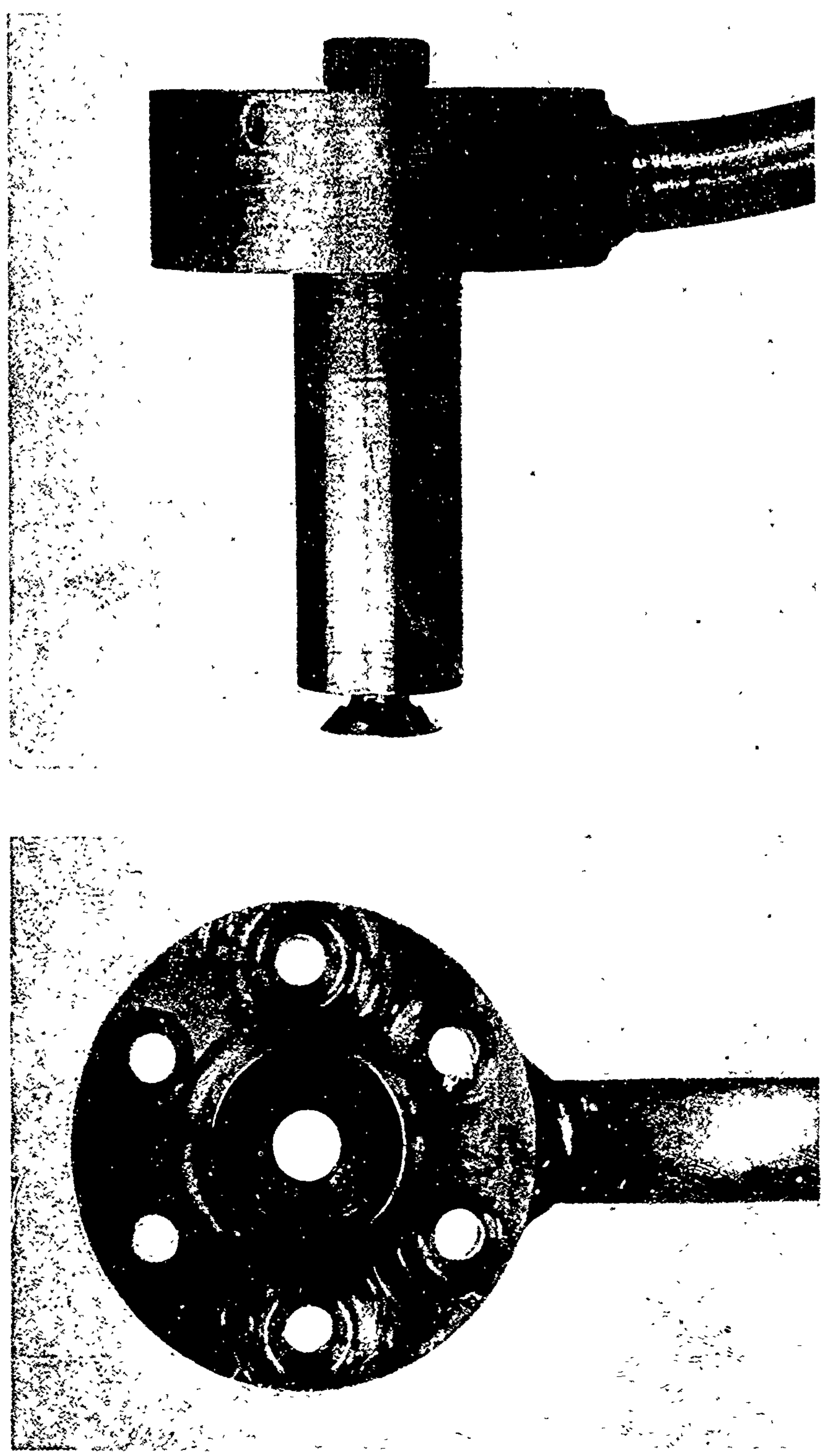


Figure 52. (U) Dual-Manifold Injector

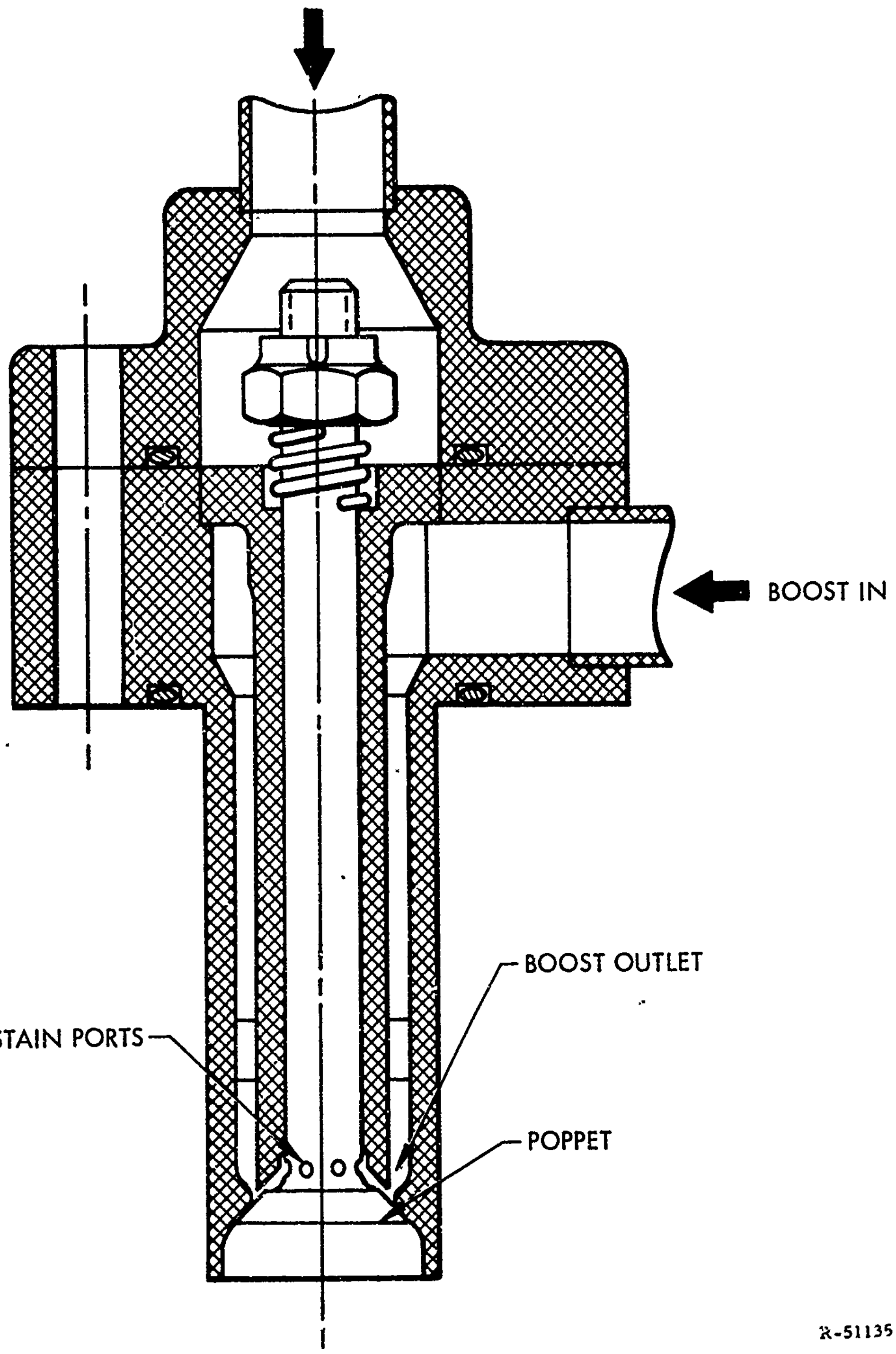


Figure 53. (U) Dual-Manifold Poppet Injector

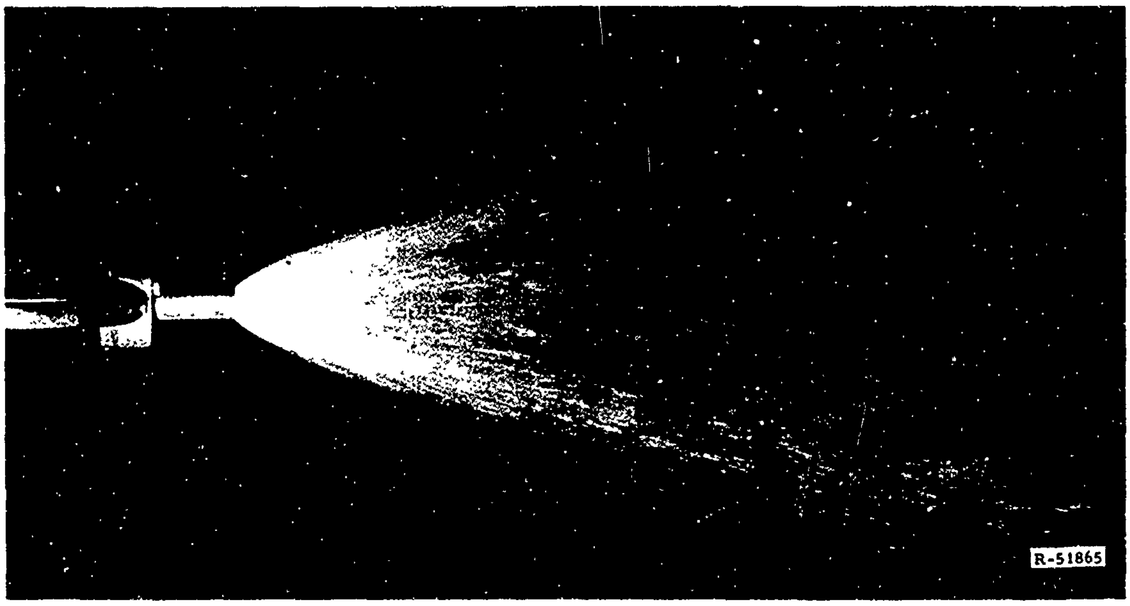


Figure 54. (U) High Flow Rate Dual-Manifold Injector Calibration

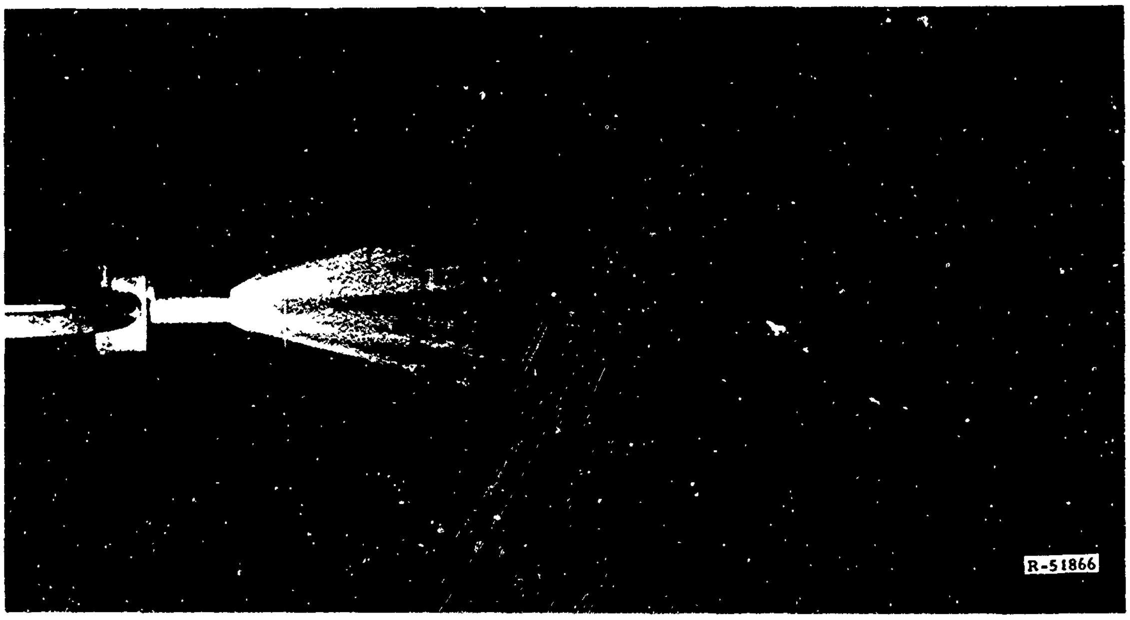


Figure 55. (U) Low Flow Rate Dual-Manifold Injector Calibration

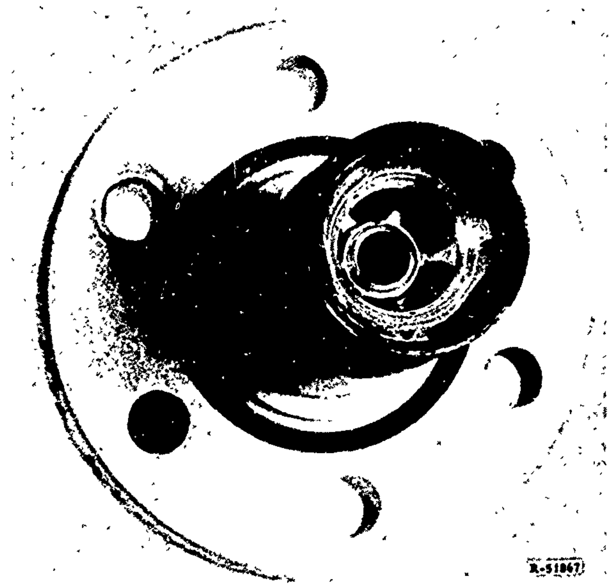


Figure 56. (U) Poppet Injector-Poppet Removed

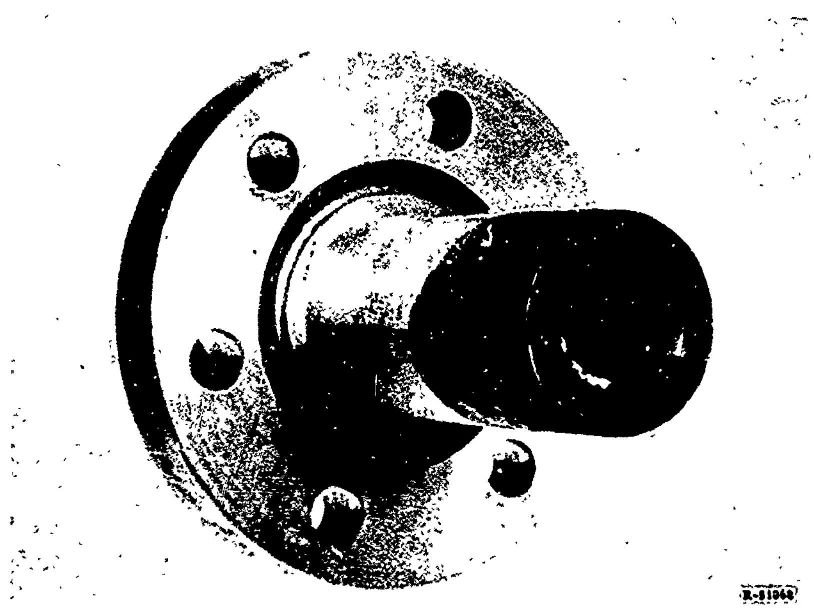


Figure 57. (U) Poppet Injector with Poppet

to limit the contamination on shutdown to external surfaces. On restarting, the contaminated external surfaces of the injectors are flushed by the oxidizer without damage to the metal surface.

(U) To complete the complement of injectors required for the selected thrust control scheme, a simple poppet-type aft injector, shown in figure 58, was developed for the full-scale motor. The aft injector was successfully tested in a full-scale motor test of 15-sec duration.

(C) The aft injector operates on oxidizer fluid pressure, but in this case it also acts as a fixed-area orifice. Flow rate variation through the aft injector is therefore accomplished only by changes in the pressure differential. The aft injector is designed to deliver 120° included angle radial spray pattern to deliver oxidizer into the motor plenum chamber from its central location. Flow rate changes required for dual thrust operation are accomplished by changes in injector differential pressure.

(U) Prior to the development of the dual manifold poppet injector and poppet-type aft injector, an injector development program was conducted to evaluate various injector concepts which had potential application in a dual-thrust hybrid propulsion system. Injector requirements included the capability of delivering two oxidizer flow rates for the boost and sustain thrust levels at both primary and aft injector locations. The spray pattern should have a minimum of radial spray momentum in order to minimize splashblock requirements and effect uniform fuel regression behavior. In addition, the injectors should be capable of multiple motor restarts after short coast periods.

(U) Several injector designs were evaluated which had one or more of the desirable features of a dual-thrust motor injector. In addition, a concept which will allow a single primary injector to be used with multiple port fuel grains was evaluated.

(U) Although they are not used in the full-scale motor, the injectors tested contributed to the evolution of the dual manifold and aft poppet injectors used in the full-scale motor. A description of each injector tested is therefore included in this report.

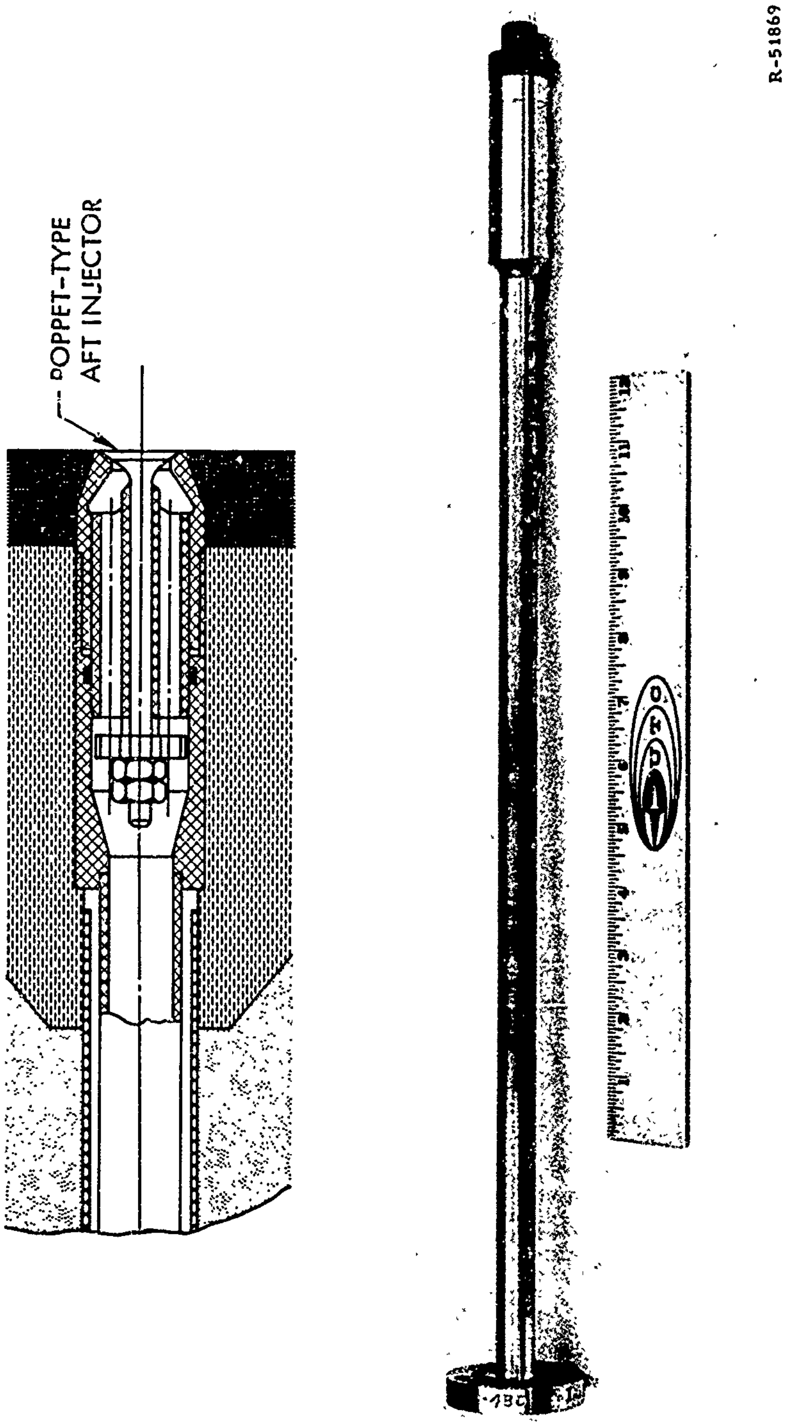


Figure 58. (U) Aft Injector

c. Impinging Streams Injector

(C) The impinging streams injector, shown in figure 59, was designed to provide an axial oxidizer flow distribution and thereby eliminate the requirement of shielding the injector with graphite and the necessity for including a low burning rate splashblock in the motor designs, in order to obtain uniform fuel regression behavior. Both shielding and splashblock have been required previously to obtain an axial spray pattern.

(C) The injector is regeneratively cooled by flow passages just behind the face. The face is anodized to provide insulation between the combustion zone and the injector.

(C) The impinging streams injector was tested in 5.0-in. motor hardware for 10-sec durations at a chamber pressure of 300 psia. The oxidizer flow rate was 2.0 lb/sec with an injector pressure drop of 50 psi. The injector did not experience any damage. Further development with this injector was

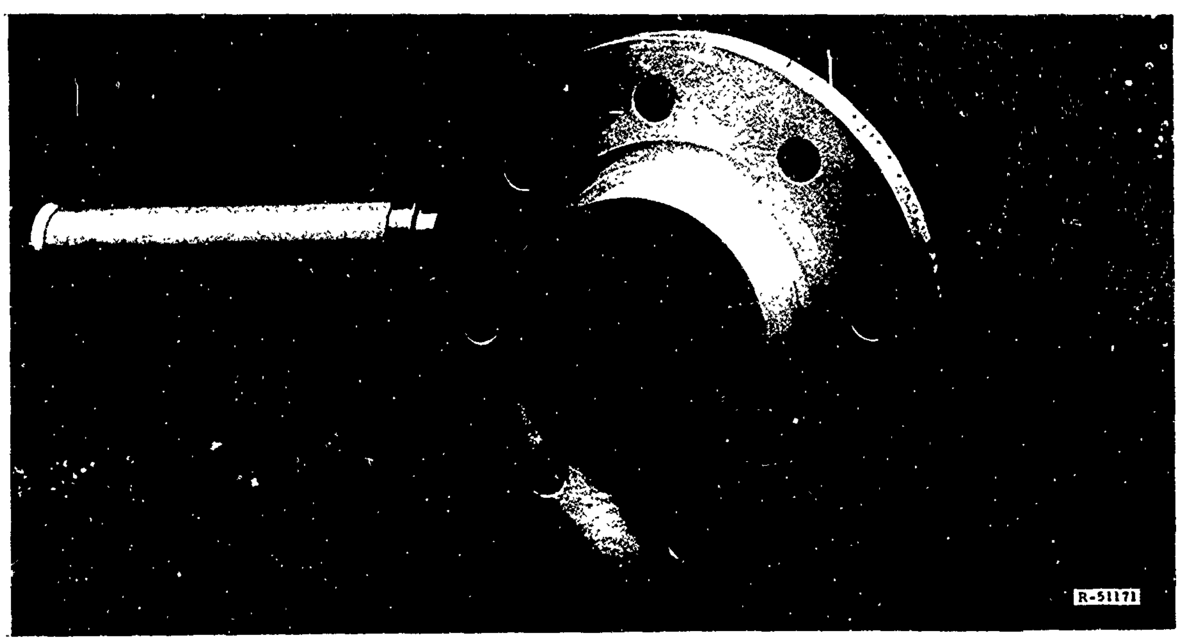


Figure 59. (U) Multiple Impinging Streams Injector

discontinued, as dual-thrust injectors described in the following paragraphs can better accomplish the injector requirements. However, the development of this injector has provided important data on regenerative cooling and anodized shielding.

d. Dual-Orifice, Hollow-Cone Injector

(C) The dual-orifice, hollow-cone injector, shown in figure 60, provides two oxidizer flow rates at a fixed pressure differential. Two concentric hollow-cone injector elements provide oxidizer flow through both the inner orifice and outer annulus during boost thrust levels and through the inner orifice during the sustaining thrust levels. The injector was used successfully in a test of 10-sec duration, which included 5 sec at 150 psi with an oxidizer flow rate of 0.5 lb/sec and 5 sec at 500 psi with an oxidizer flow rate of 2.0 lb/sec. This injector design could be used in full-scale motor development after modifications are made to provide an axial oxidizer-spray pattern and shutoff capability.

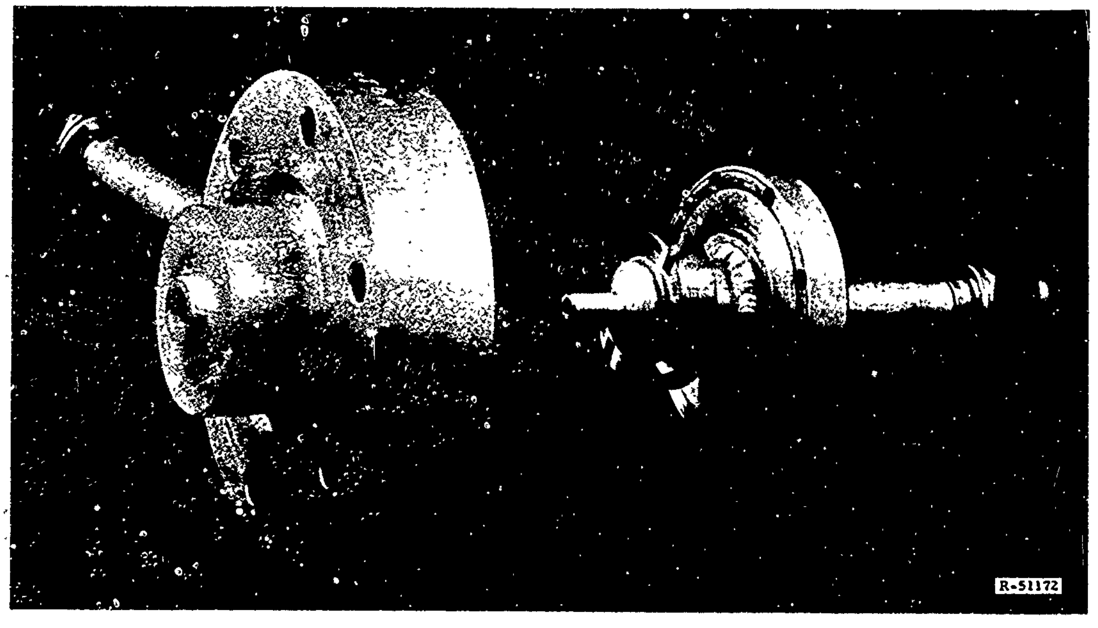


Figure 60. (U) Dual-Orifice, Hollow-Cone Injector

discontinued, as dual-thrust injectors described in the following paragraphs can better accomplish the injector requirements. However, the development of this injector has provided important data on regenerative cooling and anodized shielding.

d. Dual-Orifice, Hollow-Cone Injector

(C) The dual-orifice, hollow-cone injector, shown in figure 60, provides two oxidizer flow rates at a fixed pressure differential. Two concentric hollow-cone injector elements provide oxidizer flow through both the inner orifice and outer annulus during boost thrust levels and through the inner orifice during the sustaining thrust levels. The injector was used successfully in a test of 10-sec duration, which included 5 sec at 150 psi with an oxidizer flow rate of 0.5 lb/sec and 5 sec at 500 psi with an oxidizer flow rate of 2.0 lb/sec. This injector design could be used in full-scale motor development after modifications are made to provide an axial oxidizer-spray pattern and shutoff capability.

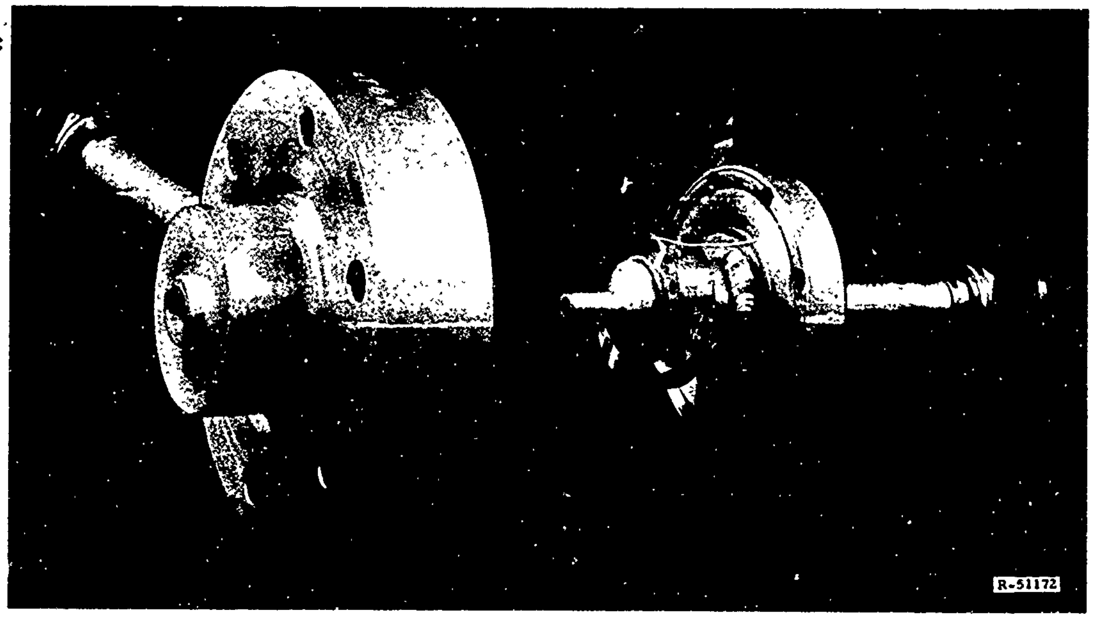


Figure 60. (U) Dual-Orifice, Hollow-Cone Injector

e. Poppet Injector

(C) Conventional injectors may be subject to fuel vapor backflow after motor shutdown which could cause injector failure during an attempted restart. Two poppet-injector concepts were developed and successfully tested which provide injector-face shutoff of oxidizer and eliminate possible injector-failure problems during motor restart. The injector shown in figure 61 is a simple spring-loaded poppet which opens to the calibrated stop position under fluid pressure. When oxidizer flow is terminated by upstream control valves, the poppet injector closes, preventing fuel vapor backflow, trapping oxidizer in the feed lines, and producing immediate thrust termination. Axial flow is achieved by flow deflectors built into the injector.

(U) The poppet injector was successfully tested in a 10-sec duration motor firing at an oxidizer flow rate of 2.0 lb/sec and a chamber pressure of 300 psi.

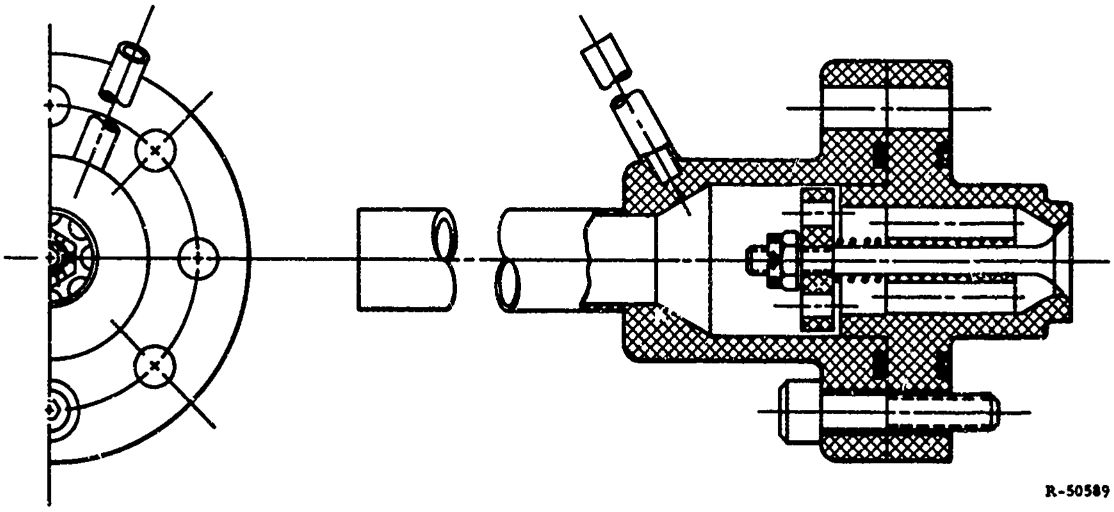


Figure 61. (U) Poppet Injector

f. Orificed-Poppet Injector

(U) A second poppet injector, shown in figure 62, was tested which incorporates orifices to control oxidizer flow rate. The injector is opened by fluid pressure to a position which allows free oxidizer flow from the orifices. The flow is then directed axially by self-cooled deflecting surfaces. Phenolic insulating material is installed on the injector poppet face to provide shielding. The injector has been tested twice at an oxidizer flow rate of 2.0 lb/sec.

g. Single-Point Primary Injection

(C) Two 5.0-in. motor tests were conducted to evaluate the feasibility of using a single injector to supply oxidizer to multiple-port fuel grains via a common head-end plenum. Oxidizer (ClF_3) was supplied at a flow rate of 1.18 lb/sec through a single spring-loaded poppet injector to a three-spoke fuel grain shape. A plenum was formed by the head-end insulation and fuel grain insulating shield (see figure 63). A high regression

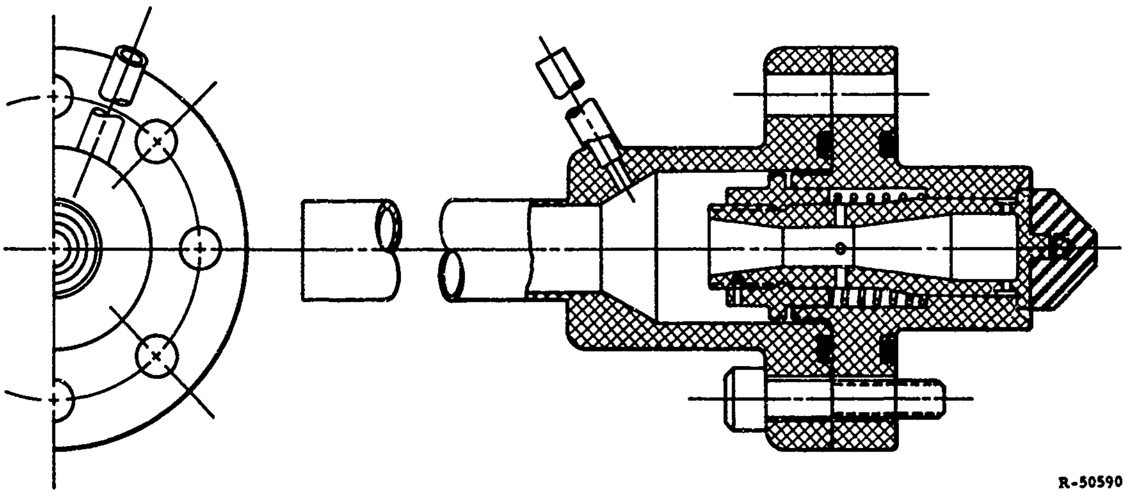


Figure 62. (U) Orificed-Poppet Injector

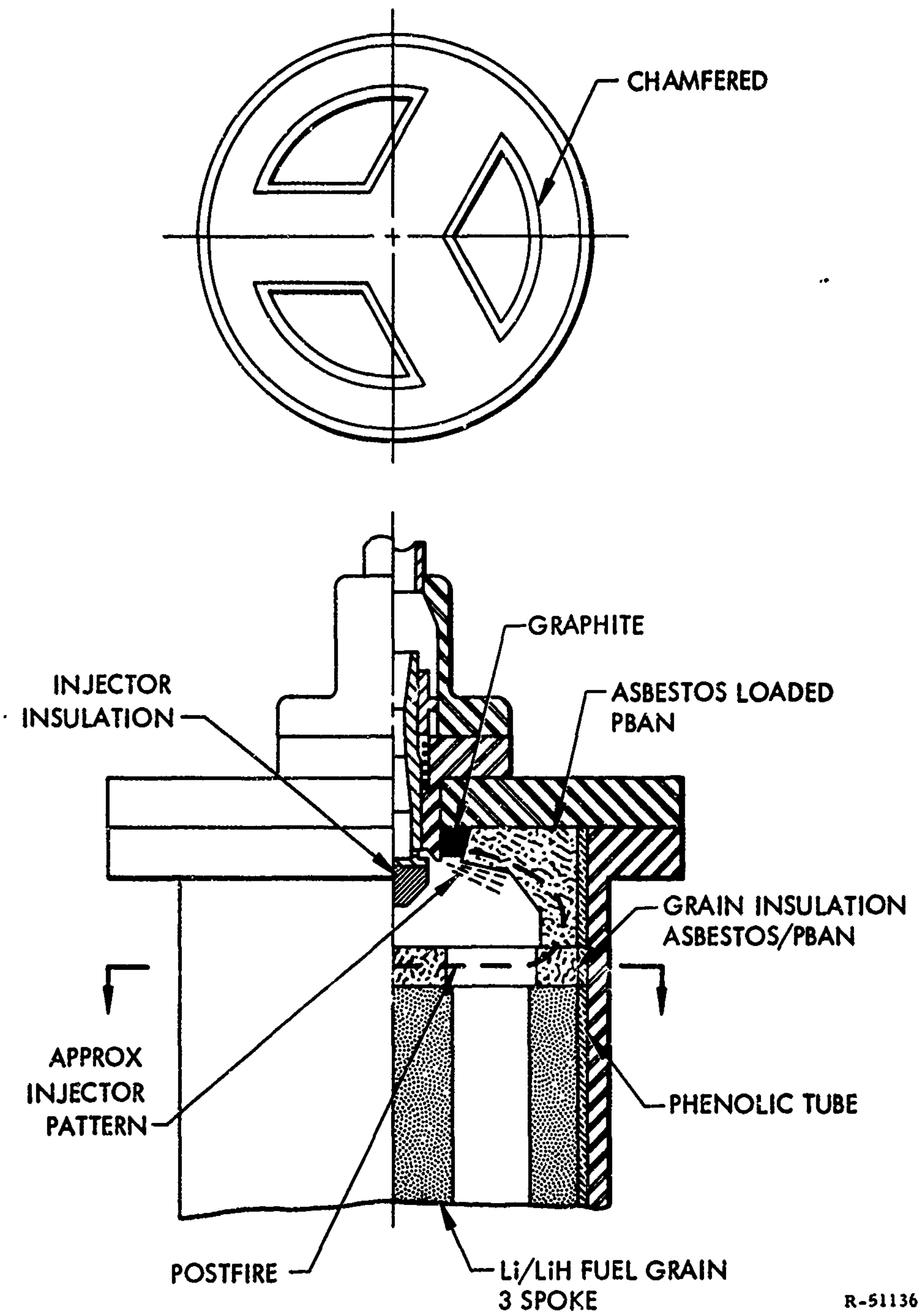


Figure 63. (U) Motor Configuration, Single-Port Injection Test

rate resulted at the head end of the motor during the first 5-sec test. The high regression rate was caused by flow recirculation created when the insulating shield eroded at a lower rate than the fuel grain. The second test was made with a 1/4-in.-thick insulation which eroded at a rate equal to that of the fuel. Uniform fuel regression was obtained and the fuel was completely consumed, except for the anticipated sliver (see figures 64 and 65). These tests indicate that the concept is feasible and could greatly simplify oxidizer injection. No further work was conducted, since the development work required would not be possible within the present contract period. (C)

2. THRUST CHAMBER

(U) An 18-in.-diameter full-scale hybrid thrust chamber was designed, fabricated, and tested during this program. Seven motor assemblies, including three versions of the thrust chamber, were fabricated and three were tested for durations up to 15 sec.

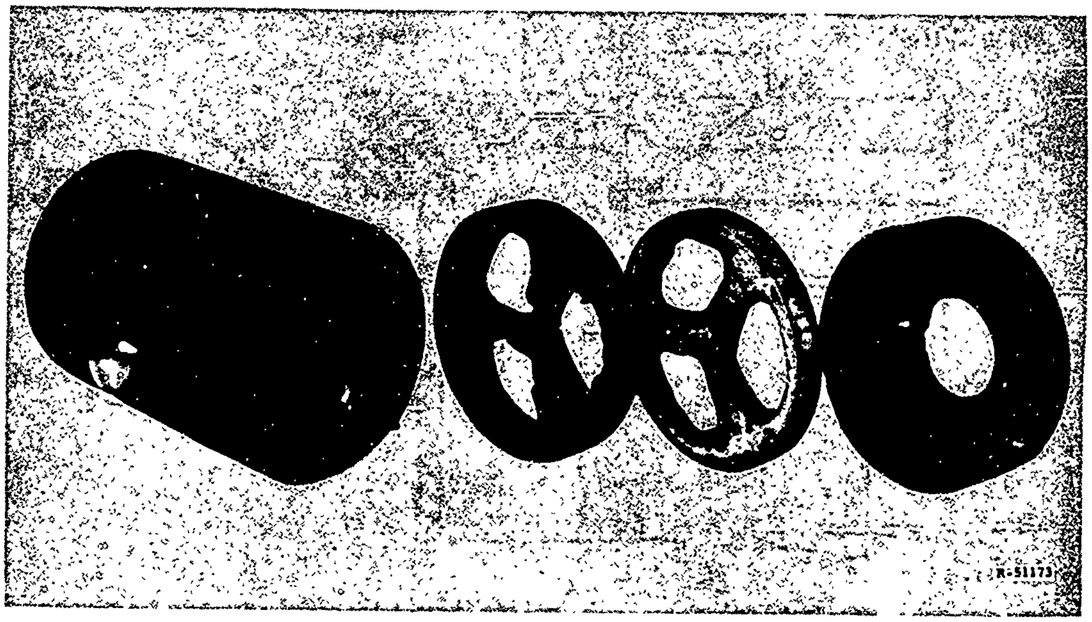


Figure 64. (U) 5.0-in. Three-Port Fuel Grain After Test No. 1

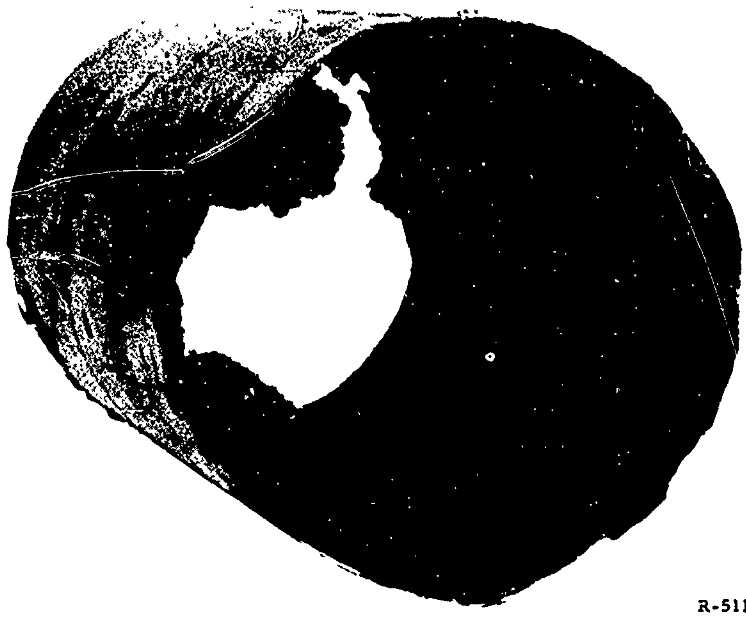


Figure 65. (U) 5.0-in. Three-Port Fuel Grain After Test No. 2

(C) The thrust chamber is designed to operate at a chamber pressure of 1,000 psi at boost thrust and 500 psi at sustain thrust. The chamber contains approximately 240 lb of fuel. It incorporates six dual flow primary injectors located in the forward closure and an aft injector attached to the forward closure by a feed tube which passes through the center of the fuel grain. The injector sprays oxidizer into a plenum chamber formed by the aft surface of the fuel grain, the aft closure, and a buried nozzle. The initial version of the motor, designated Mark I, is shown in figure 66. Subsequent designs designated Mark I-A, also shown in figure 66 and Mark II shown in figure 67, incorporated changes in the aft closure insulation and forward closure design.

(U) Nine motors were fabricated in the three configurations. Table XVI lists the motors and their present status.

(C) The Mark I configuration was designed and fabricated using preliminary materials data. Subsequent tests indicated a need for materials and design changes as outlined in the following sections of this report. These changes included changes in aft closure material to reduce heat retention and rubber case liners to prevent internal gas leaks. The modifications accomplished on existing Mark I hardware produced the Mark I-A configuration. Meanwhile, thermal analyses initiated at the start of the program

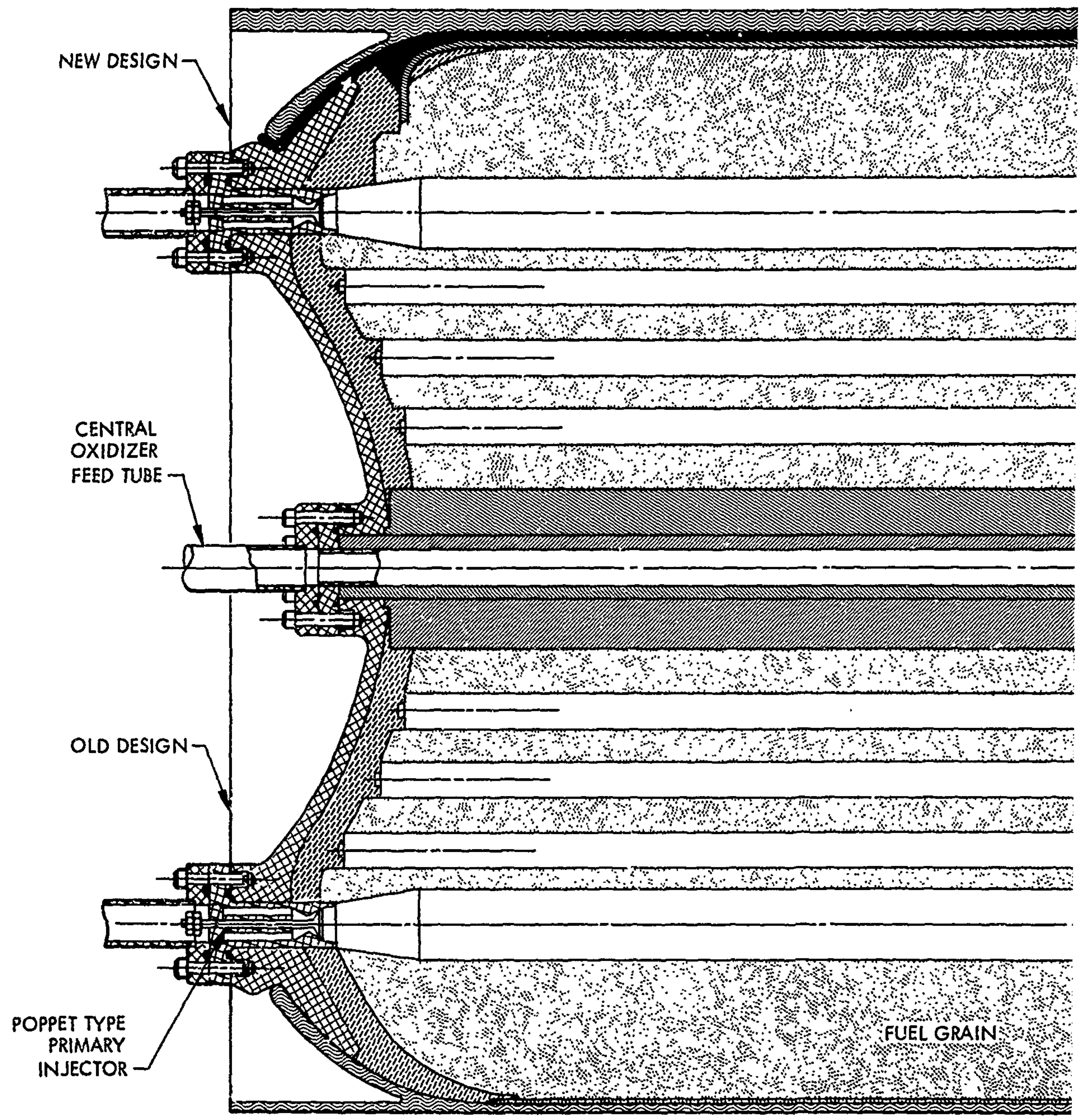
TABLE XVI

(U) FULL-SCALE THRUST CHAMBERS

Motor No.	Configuration	Status
001	Mark I	Tested; resulted in motor case failure
002	Mark I	Hydrotested to failure
003	Mark I	Tested at sustain thrust for 15-sec duration
004	Mark I-A	Motor assembled; fuel porous; motor being held pending disposition
005	Mark I-A	Motor assembled; fuel porous; motor being held pending disposition
006	Mark I-A	Motor assembled; fuel cast, case leak, awaiting disposition
007	Mark II	Motor tested 5.0 sec; demonstrated boost and sustain thrust operation
008	Mark II	Fabricated — not assembled
009	Mark II	Fabricated — not assembled

was completed in the light of the new data, indicating that noncharring ablative materials were needed. These analyses resulted in the Mark II motor configuration, which include a noncharring nylon phenolic aft closure insulation which has been determined to be essential for rapid combustion termination, a new nozzle, and a forward closure with attached thrust control valve.

(C) The motor is assembled by installing prefabricated forward and aft closure assemblies on an assembly mandrel over which a filament wound case is applied. Filament wrapping of motor cases provides a means of producing a lightweight flight configuration test motor which is essential to obtain precise motor weight data and to determine fuel flow accurately. The motor is assembled and wrapped with casting mandrels made of Woods metal installed in the completed motor assembly. To extract the casting mandrels after the fuel is cast and cured, the curing-oven temperature is increased to the melting temperature of the Woods metal (160° F), and the mandrels are melted out.



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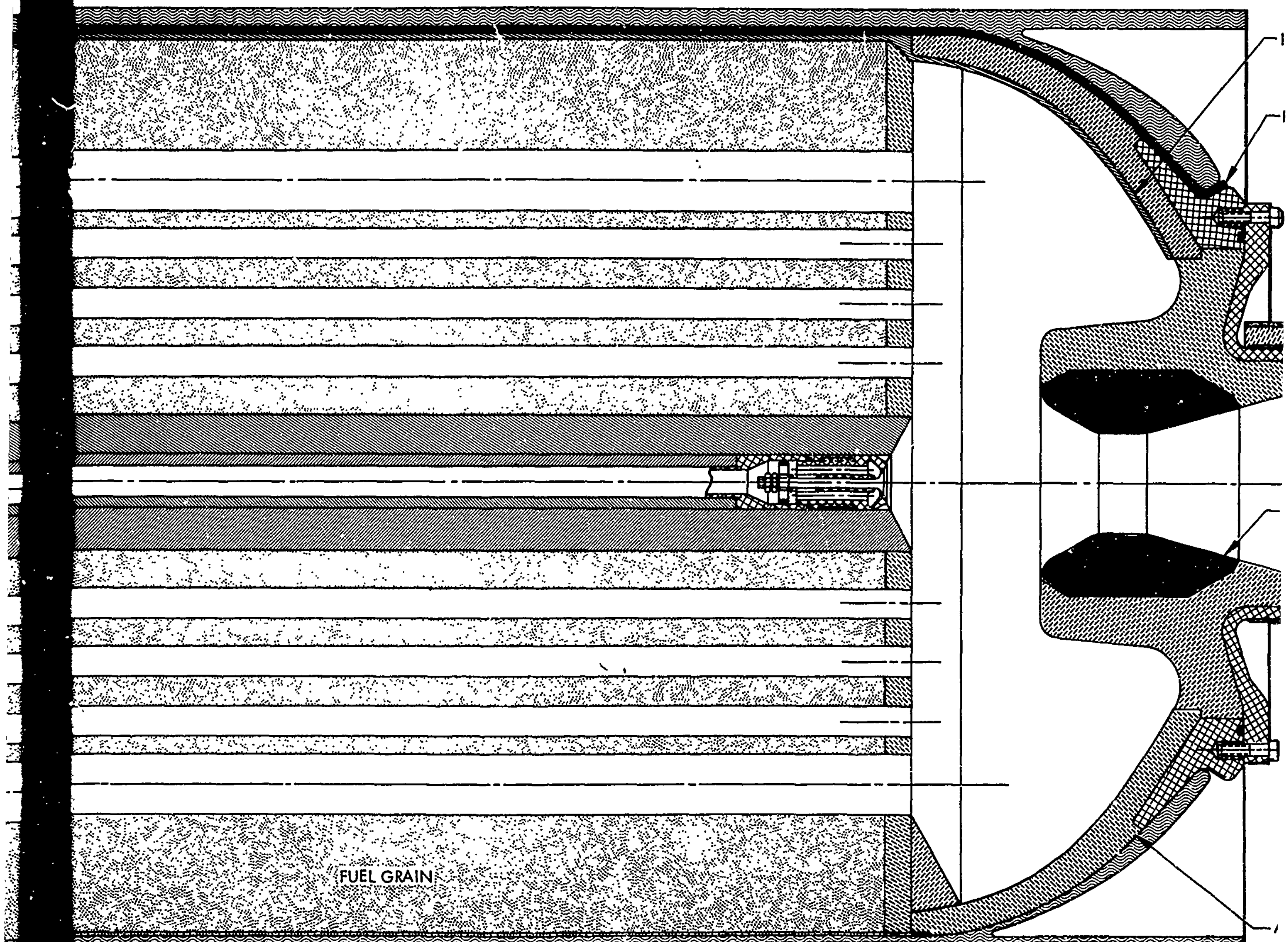


Figure 6
Filamer

1 2

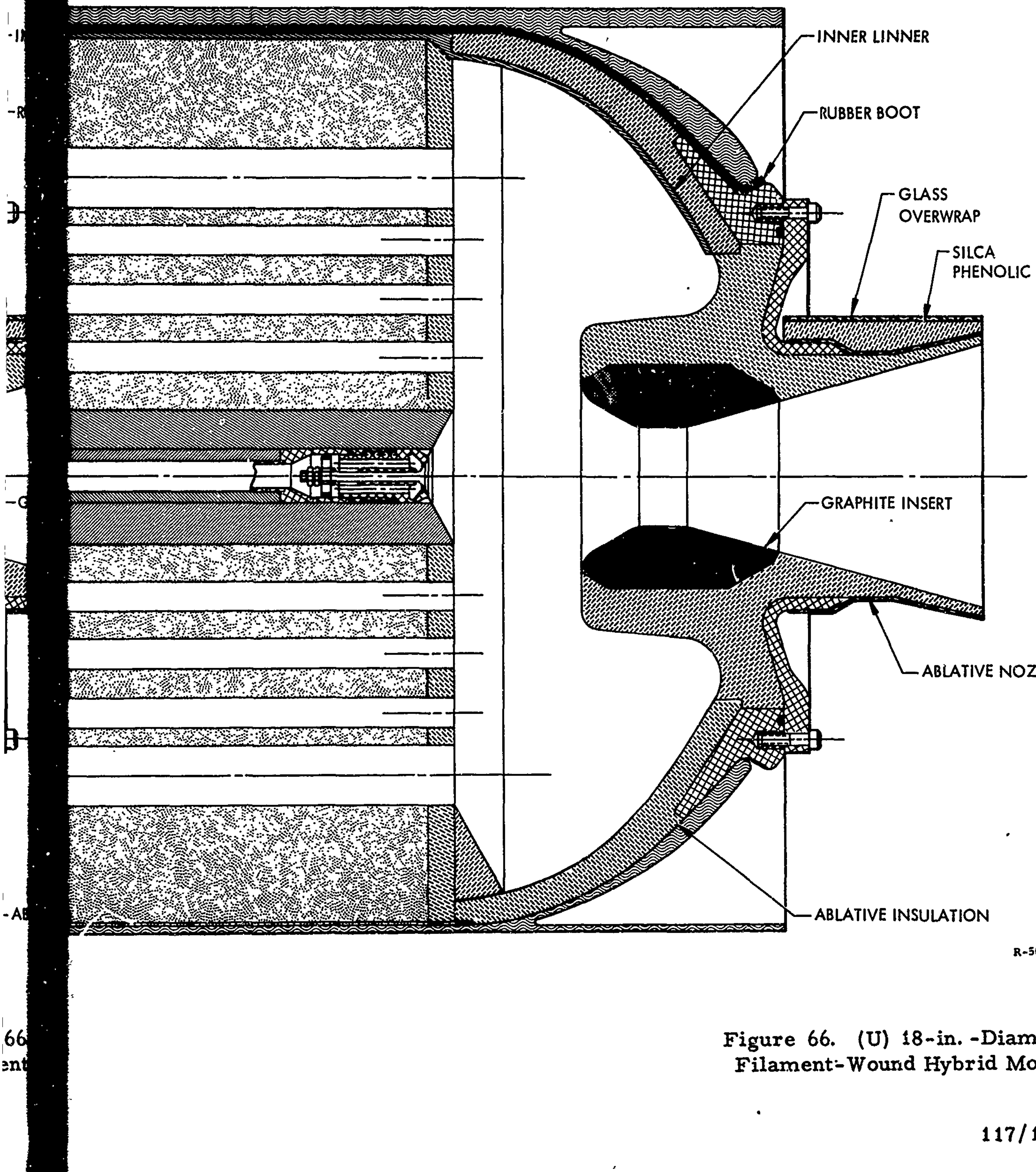
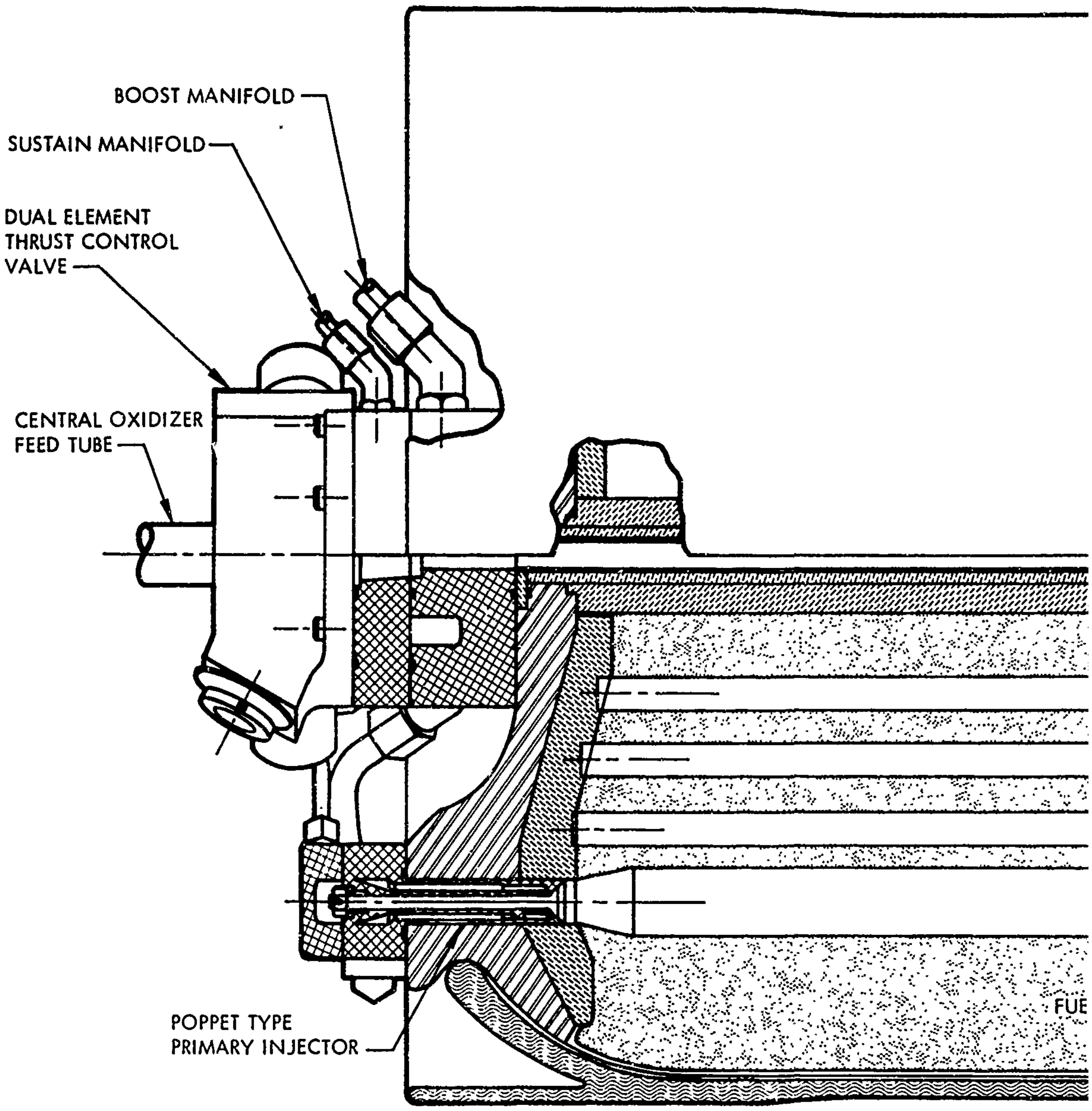


Figure 66. (U) 18-in. -Diameter Filament-Wound Hybrid Motor



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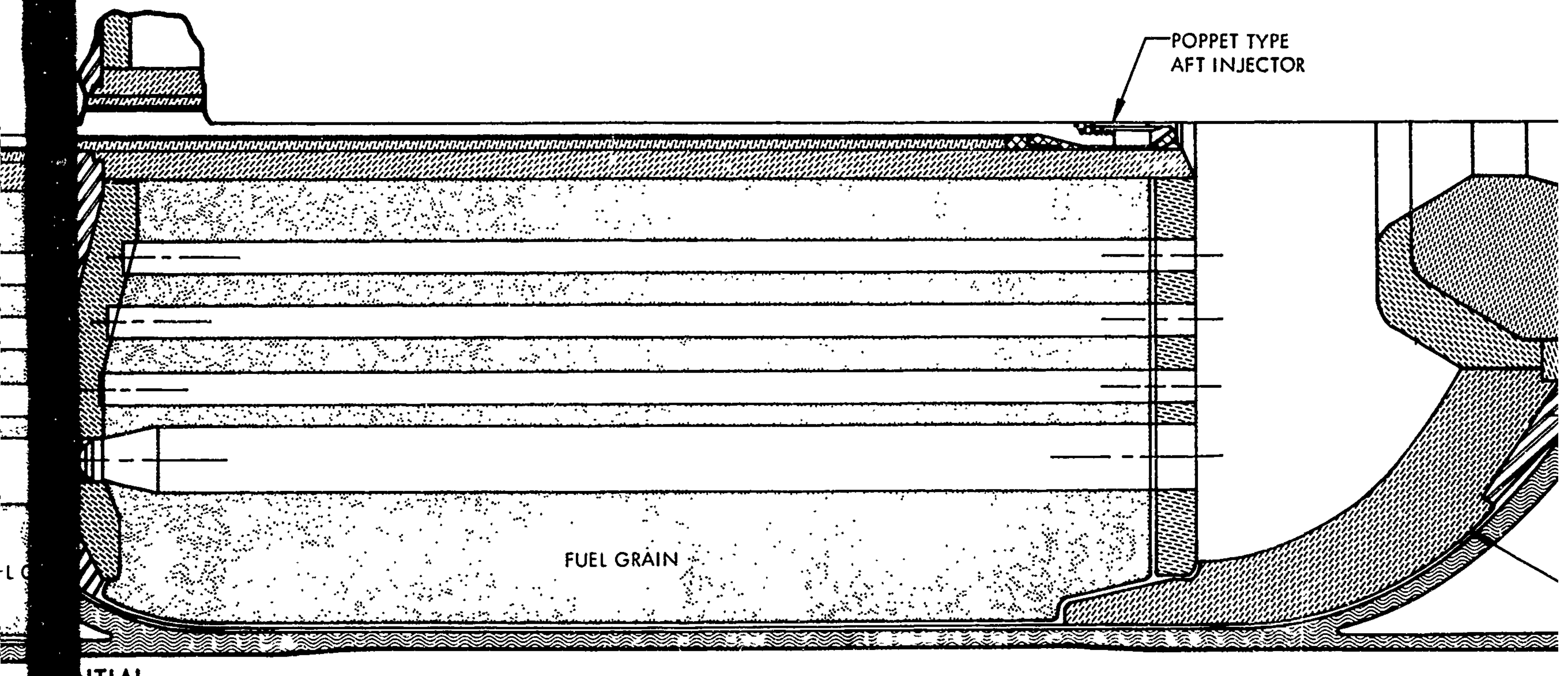

Figure 67.
Filament-
Mark

1

2

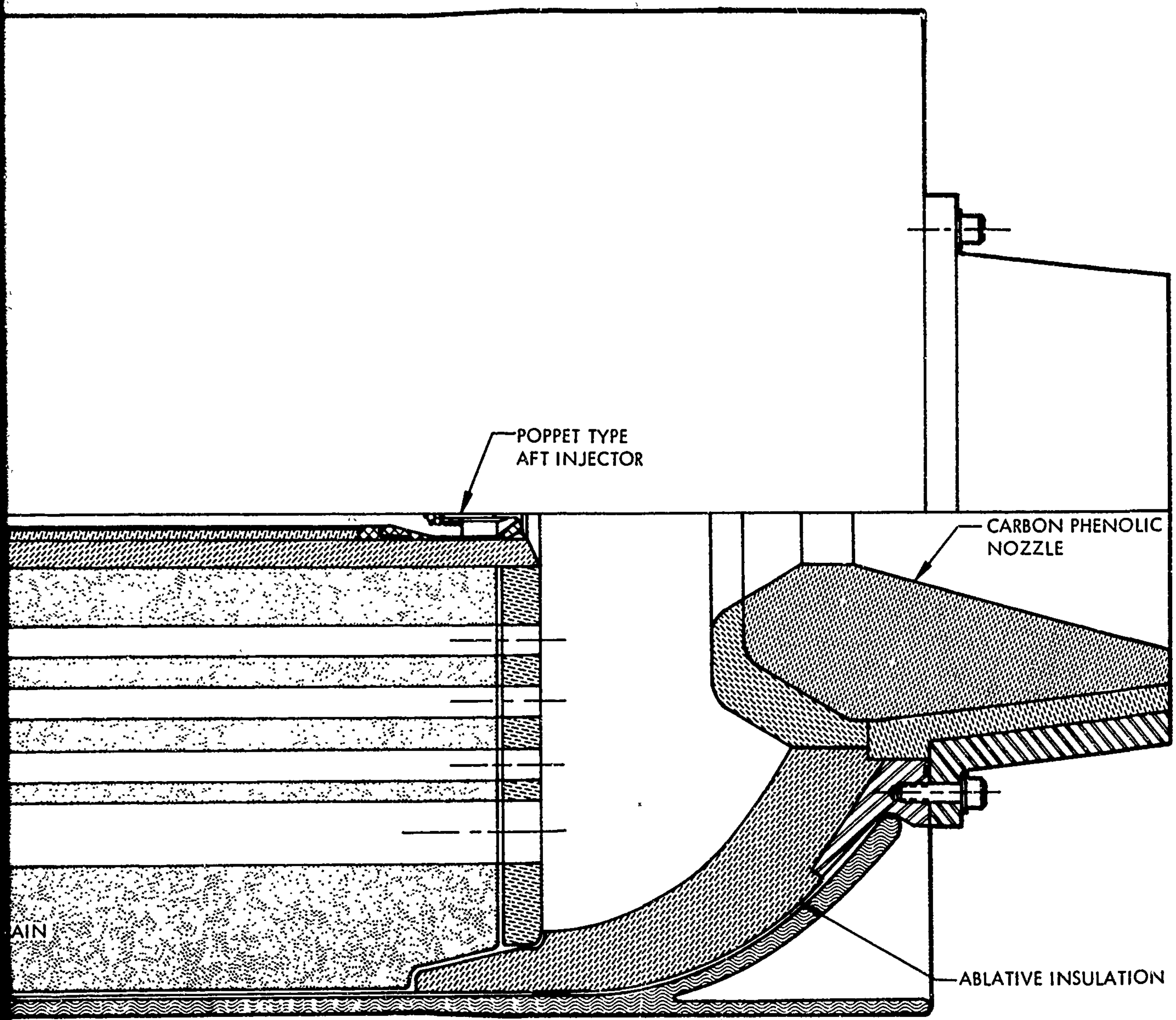

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Figure 67. (U) 18-in. -Diameter Filament-Wound Hybrid Motor Mark II Configuration

2 3

(C) The motor uses a centrally located aft injector and a plenum created by the buried nozzle to produce efficient mixing and obtain high performance. These previously tested techniques to obtain high performance levels, were tested on Contract AF 04(611)-8516 using the motor configuration shown in figure 68 and on Contract NAS 7-311 using the configuration shown in figure 69.

(C) The first motor used a plenum chamber created by a simulated buried nozzle to change abruptly the direction of flow of the coaxial fuel and oxidizer streams, thereby inducing mixing in the plenum sufficiently to deliver a specific impulse of 91% of theoretical.

(C) The second motor used a centrally located, radial spray aft injector to produce the necessary mixing in a small, aft plenum chamber. Performance levels of approximately 94% of theoretical specific impulse have been achieved using this configuration.

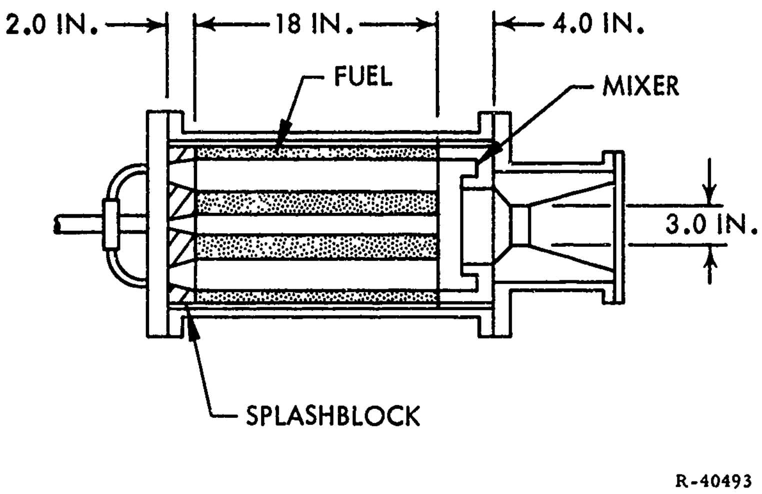
3. MARK I MOTOR

(C) The Mark I thrust chamber design incorporated forward and aft closures fabricated of aluminum and insulated with buna-N modified carbon cloth-phenolic and asbestos-phenolic insulation. Because of its resistance to the high temperature environment, the carbon cloth-phenolic material was used in the plenum chamber where the chamber wall is exposed to the combustion gases. However, the relatively high conductivity of the carbon cloth-phenolic material requires that it be backed by a reinforcing of an insulating layer of asbestos-phenolic material. The Mark I aft closure is shown in figure 70.

(C) The nozzle assembly, also shown in figure 70, uses both insulating materials, and, in addition, uses an ATJ graphite-throat insert. The Mark I motor (No. 003) was successfully fired at nominal sustain thrust chamber pressure for a duration of 15 sec. The purpose of the test was to provide fuel flow rate, combustion data, and preliminary materials evaluation data for subsequent Mark II aft closure and nozzle designs.

(C) Scheduled tests of the same motor were canceled when a postfire inspection of the aft closure revealed surface blistering of unknown depth (shown in figure 71) into the carbon phenolic material. The material was originally selected because of its high resistance to erosion, as determined by subscale tests described in appendix I of this report.

(C) The blistering resulted not from erosion but from subsurface outgassing of the volatile materials in the closure. Blistering and delamination was due to the parallel-to-surface orientation of the carbon cloth



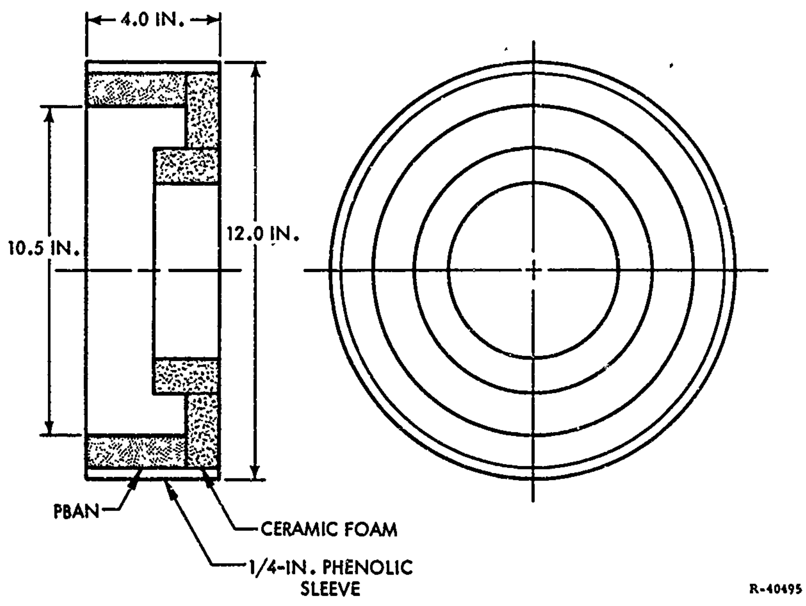


Figure 68. (U) 12-in. Motor with Simulated Submerged Nozzle

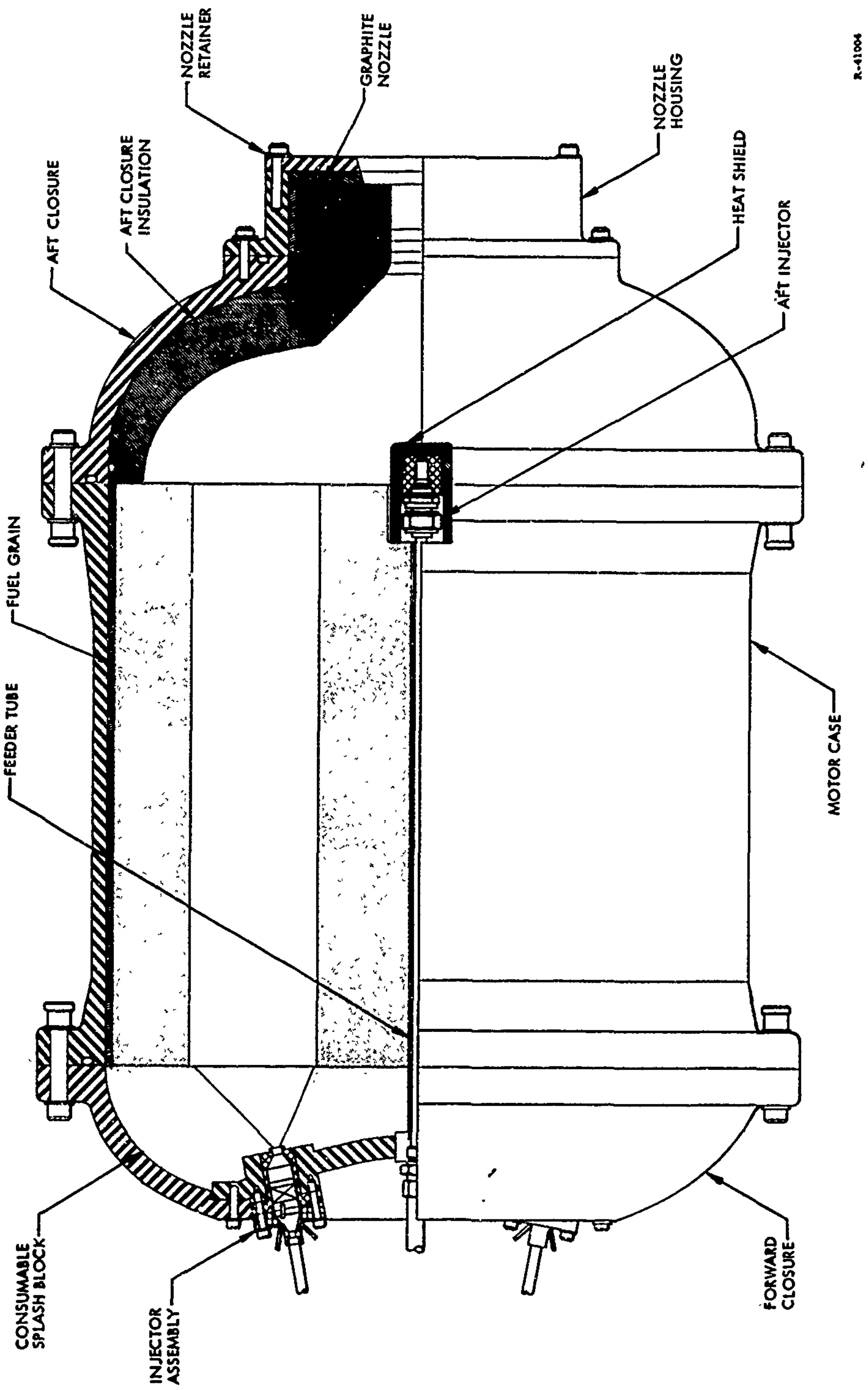


Figure 69. (U) 22-in. -Diameter Hybrid Motor

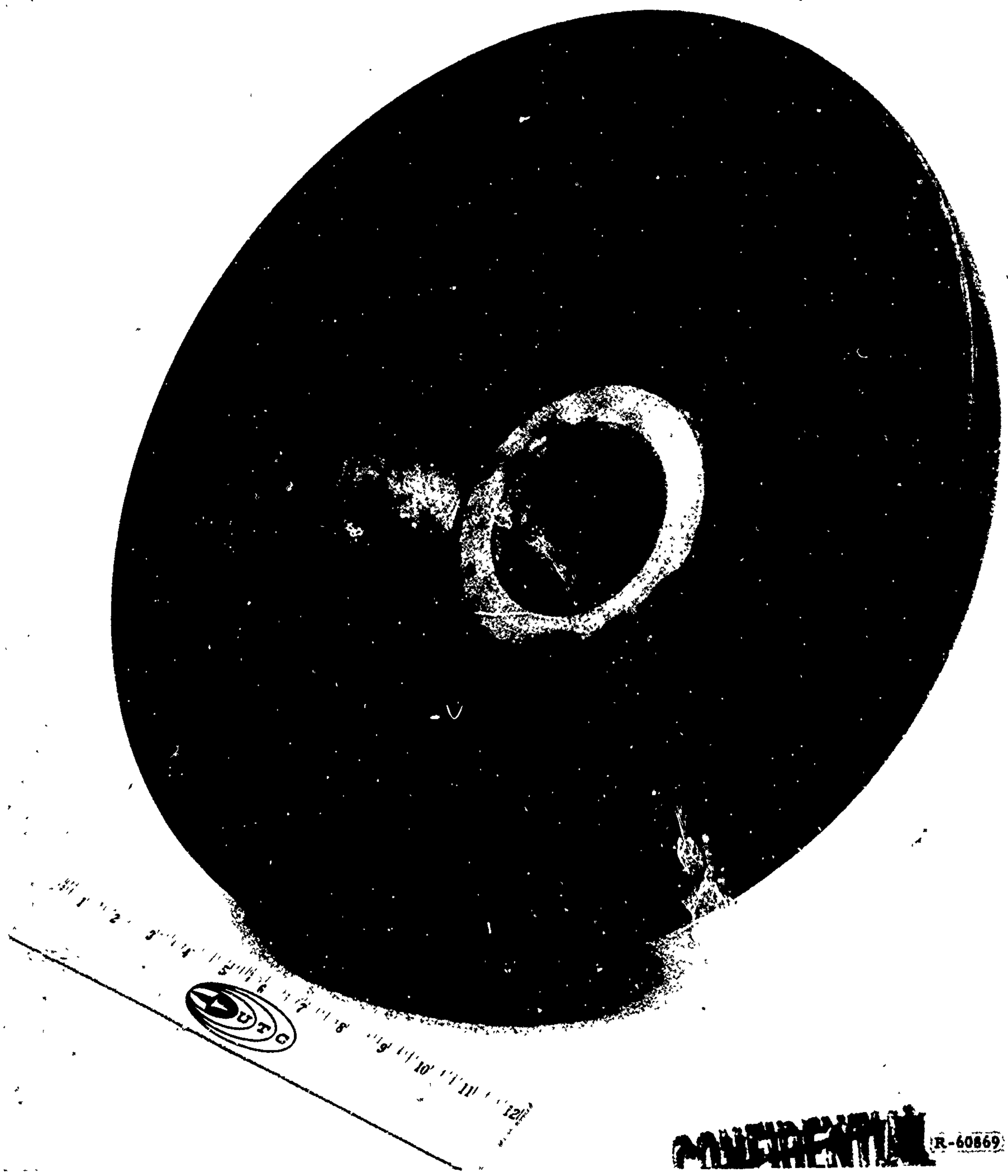


Figure 70. (U) Mark I Configuration Aft Closure and Nozzle

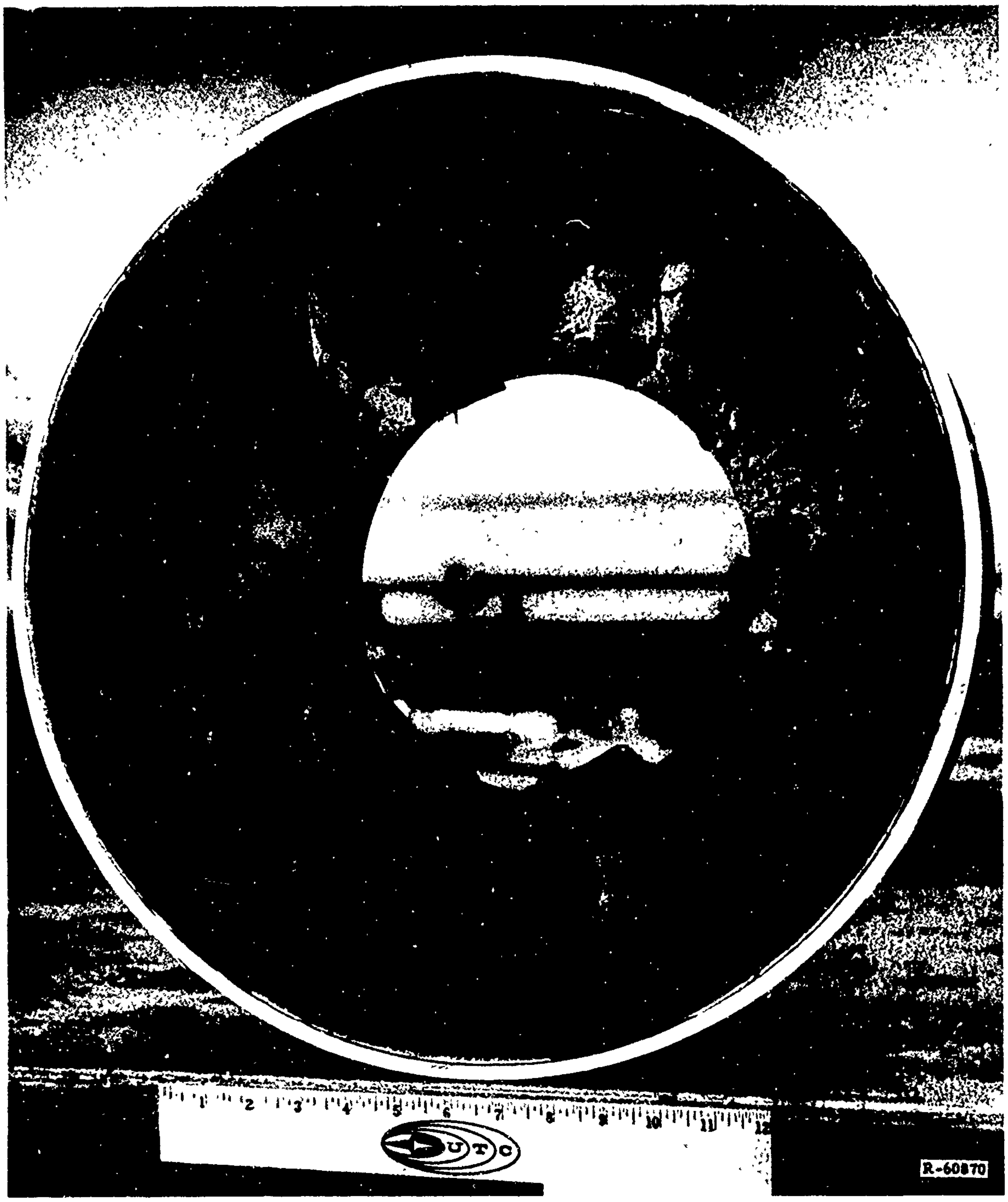


Figure 71. (U) Mark I Aft Closure Configuration After Test

which failed to allow passage of the gaseous resin products The char depth in the aft closure is uniform, as shown in figure 72, and varies from 0.10 in. to 0 25 in.

(C) Subsequent subscale motor testing has indicated the necessity of using noncharring ablative materials in the aft closure to facilitate positive motor shutdown characteristics.

(C) The carbon phenolic used in the Mark I aft closure will char and store large amounts of heat during the firing, reradiating it to the fuel grain after shutdown. This property, together with its high thermal conductivity, caused the carbon phenolic to be removed from the design. Data available from tests conducted on NAS 7-311 indicated that nylon phenolic and short fiber magnesia phenolics exhibited uniform ablation and produced a very thin char. Based on this material test data, nylon phenolic was chosen for the aft closure insulation.

(C) A modification to the Mark I motor aft closure insulation was made using a nylon-phenolic/silica-phenolic composite structure designed to minimize inside and outside surface temperature efficiently. The aft closure, shown in figure 73, used nylon-phenolic rosette layup on silica-phenolic backing. Poor bonding resulted at the interface, and the composite design was replaced by an all nylon-phenolic design in the Mark II motor.

(C) The test of motor No. 003 also provided preliminary data on the nozzle design. Erosion of the nozzle throat insert, shown in figure 73, was negligible. The loss of the liner in the lightweight nozzle skirt is the result of using a thin tapewrapped liner of highly conductive material. The skirt liner charred through rapidly, greatly diminishing its mechanical integrity, and subsequently failed under the shear forces of the rocket exhaust. The high erosion at the nozzle entrance was particularly noticeable on the glass-phenolic backup to the ATJ throat section (see arrow in figure 74). Note that the heat loads on the submerged portion of the nozzle have completely charred the entrance area, as can be noted from the delamination in this area.

(C) Heavier charring resulted on the outer surface of the nozzle within the aft closure, where char depths reached 0.80 in. A higher heat load is expected in this area, but it should be noted that the orientation of the carbon phenolic is changed at the base of the nozzle to perpendicular to the surface. Material properties data indicate that the thermal conductivity along the direction of the plys is double the value normal to the ply direction. This can account for a majority of the difference at the base of the nozzle. The free-standing nozzle entrance section has, in addition to the

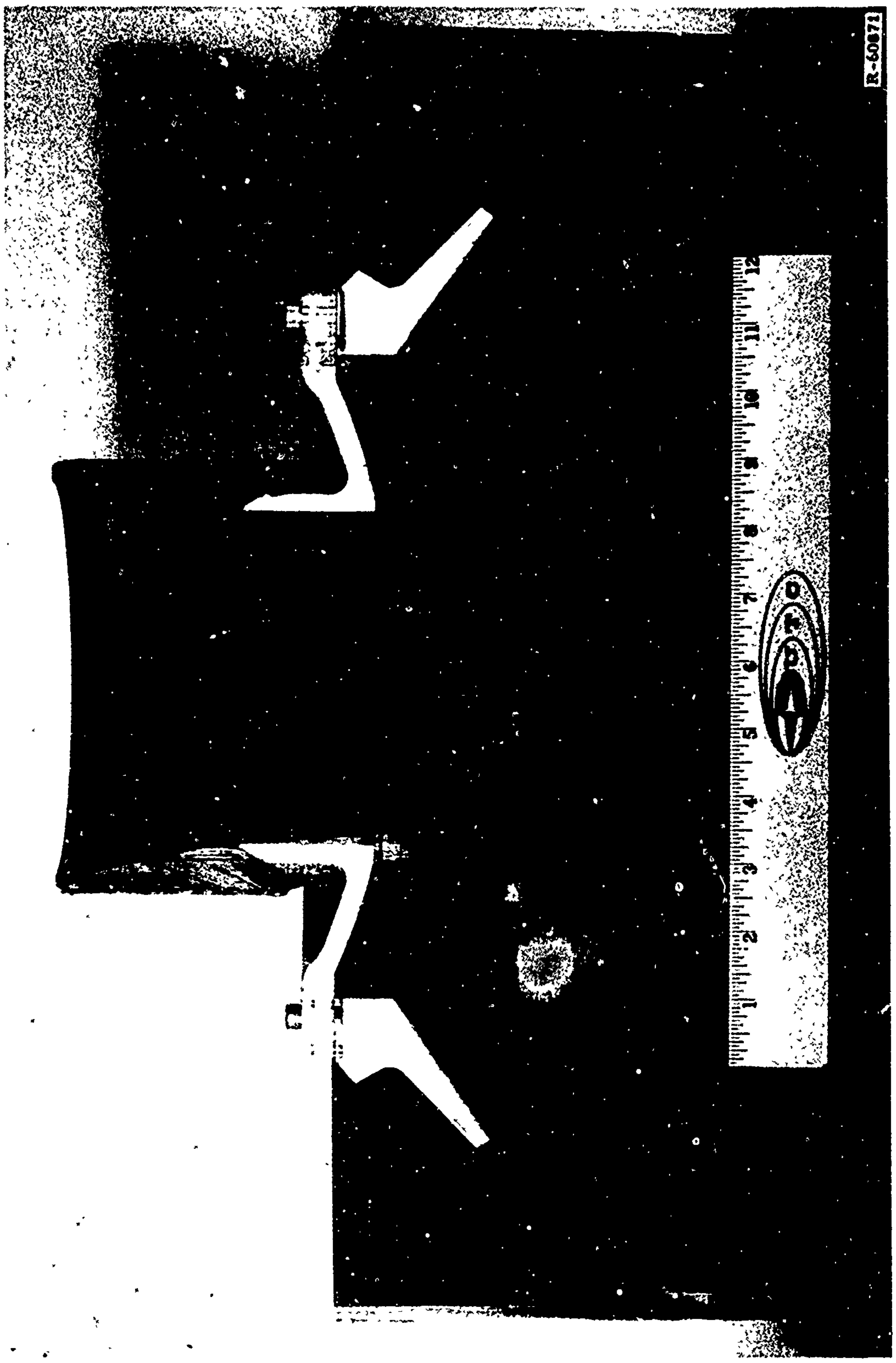


Figure 72. (U) Sectioned Aft Closure and Nozzle

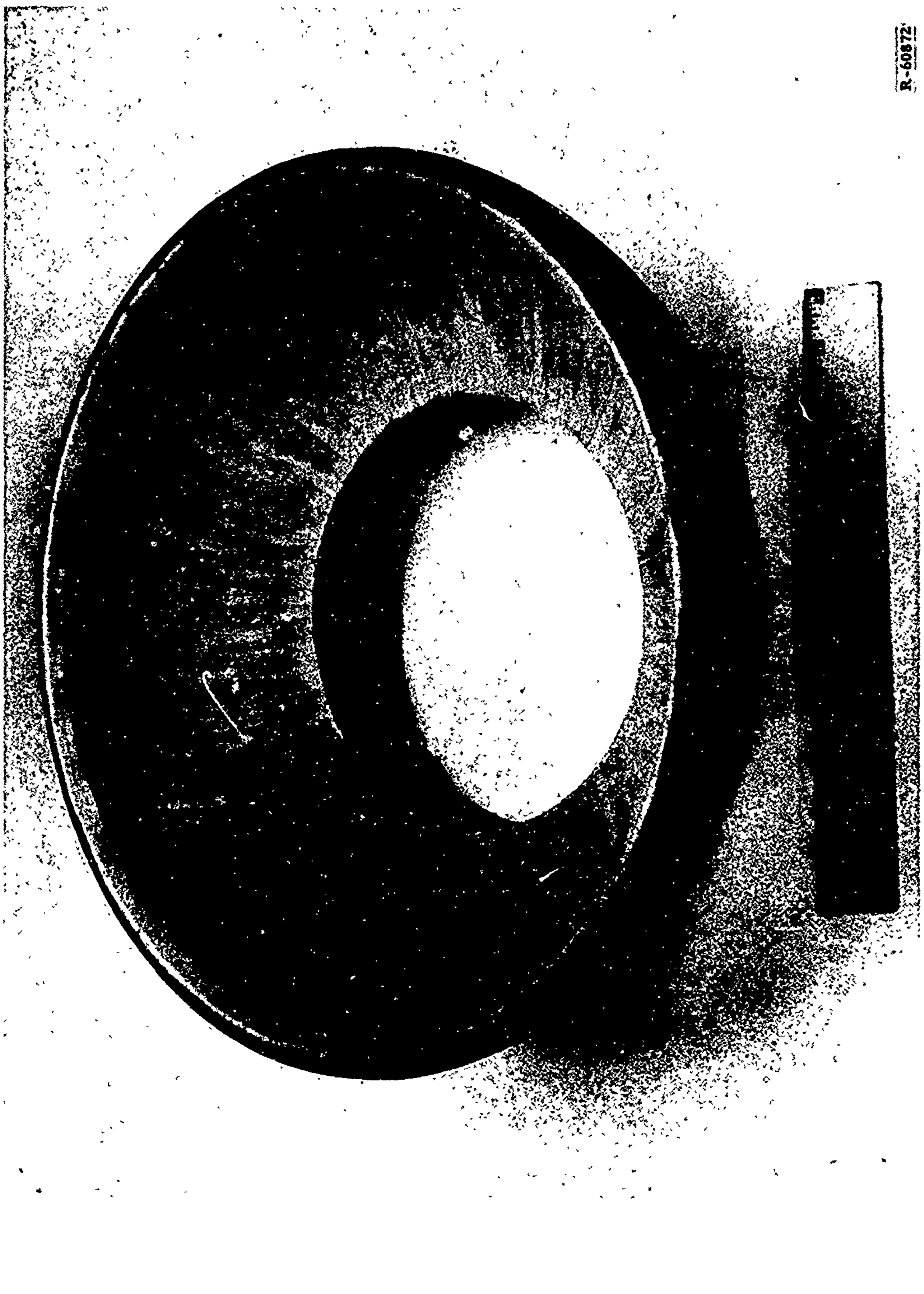


Figure 73. (U) Mark I-A Configuration Aft Closure

Figure 74. (U) Mark I Configuration Nozzle After Test

change in ply direction, a significant heat load imposed by the graphite throat insert. It was apparent from the results of motor No. 003 that in order to perform a duty cycle with repeated coast periods, a change in material and design of the aft closure and nozzle was required.

(U) Armed with preliminary materials data from motor No. 003, subscale tests conducted on this contract, and data obtained from Contract No. NAS 7-311, a thermal analysis was conducted on aft closure and nozzle assemblies.

(C) The analysis used the Mark II motor design in which nylon phenolic material of increased thickness was used for the aft closure and the graphite throat insert was removed from the nozzle. The material chosen for the nozzle throat was the graphite cloth "hi-char" phenolic combination, which performed very satisfactorily in material tests discussed in appendix I of this report. The material forms a dense char layer which exhibits superior erosion resistance and has exhibited no tendencies toward surface spalling to date.

(U) By incorporating a graphite-phenolic throat in the Mark II nozzle, the transpiration cooling effect obtained from the effluxing resin products can be used to minimize the detrimental thermal soak effects so evident with heat sink-type throats. Thermal analyses were made on several nozzle designs to evaluate their ability to withstand the repeated heat soak periods characteristic of the duty cycles required. A critical problem is the submerged portion of the nozzle, which receives severe heat loads on both the outside and inside surfaces. The design philosophy was to employ a rapid ablator to the outside of the nozzle to minimize heat input from the plenum, while the inside material (nozzle throat) was dictated by erosion resistance. Unfortunately, this results in a highly conductive throat insert. For the purpose of analysis, nylon phenolic was used as the outer heat shield on the Mark II nozzle. Further study disclosed that a nozzle failure might conceivably occur due to outgassing at its interface with the graphite-phenolic throat insert. A short-fiber magnesia-phenolic was therefore substituted for the nylon phenolic, since material test data indicate very similar ablation rates and thermal properties.

(U) In order to verify successful operation for all duty cycles, the analysis was redone with the new motor design and newly selected materials. A motor thrust duty cycle was assumed which would impose the most severe heat loads on the motor components. The thrust duty cycle assumed a 20-sec firing at a chamber pressure of 1,000 psi, a 2-min coast period, a 30-sec firing at a chamber pressure of 500 psi, a 4-min coast period, and finally a 20-sec firing at a chamber pressure of 500 psi. The following additional assumptions were made for use in the thermal analysis:

A. No heats of ablation were considered; the material was assumed to erode at experimentally determined rates.

B. No mass efflux (transpiration) from the wall was considered.

C. No heat of resin pyrolysis was considered.

D. No change in material properties was assumed to occur with the charring process.

E. No convective or radiative cooling was assumed to exist during heat soak.

F. Nylon phenolic was assumed to ablate at the equilibrium wall temperature (7,000° F).

(U) The effect of these assumptions is to produce the worst possible temperature profile and hence a conservative design.

(U) Thermal profiles were generated for the aft closure, nozzle assembly, and nozzle exit skirt at the locations shown on figure 75. The temperature profile at the start and finish of each thrust cycle is shown for each location in figures 76, 77, and 78.

(U) As can be seen from the temperature histories in the thermal profile, outside wall temperatures remain under control throughout the duty cycle. Sufficient material is present in nozzle and closure walls to ensure against the occurrence of a complete char-through during the useful life of the motor. Therefore, wall thicknesses were determined by the obtained thermal profiles. In the case of the aft closure insulation, an additional effect was considered. The NAS 7-311 material tests using nylon-phenolic aft closure insulation disclosed two distinct ablation patterns as follows; during full thrust operation, the nylon phenolic ablated uniformly at approximately 7 mils/sec; however, at minimum thrust, local erosion rates of 20 to 25 mils/sec were obtained in the port impingement area. The high erosion rates were unique with the fuel used on NAS 7-311, but the high rates were used to design the Mark II aft closure on this contract and, therefore, resulted in a conservative design. A subsequent test conducted with the Mark II motor indicates that uniform and low ablation rates are to be obtained from the nylon, but further testing is necessary to determine the required aft closure thickness.

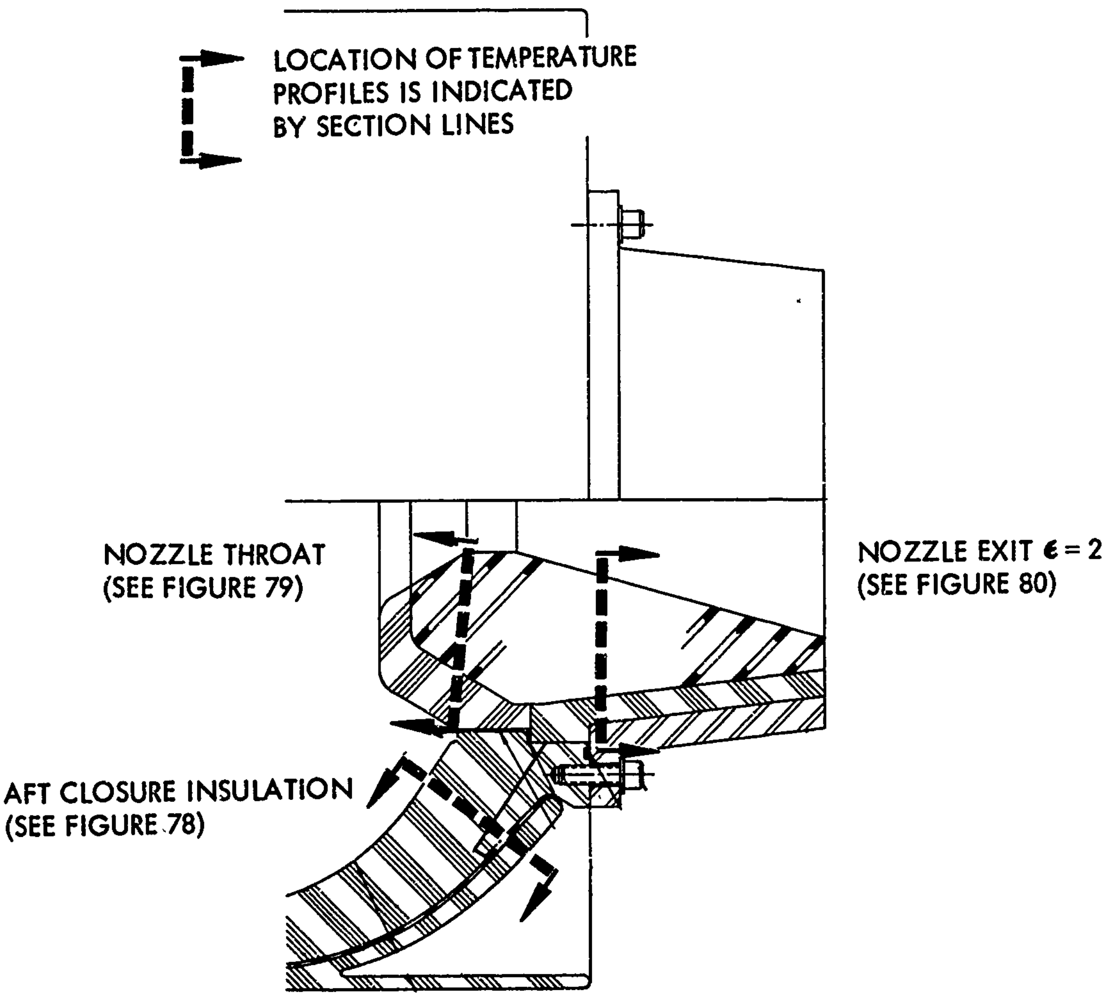


Figure 75. (U) Location of Temperature Profiles

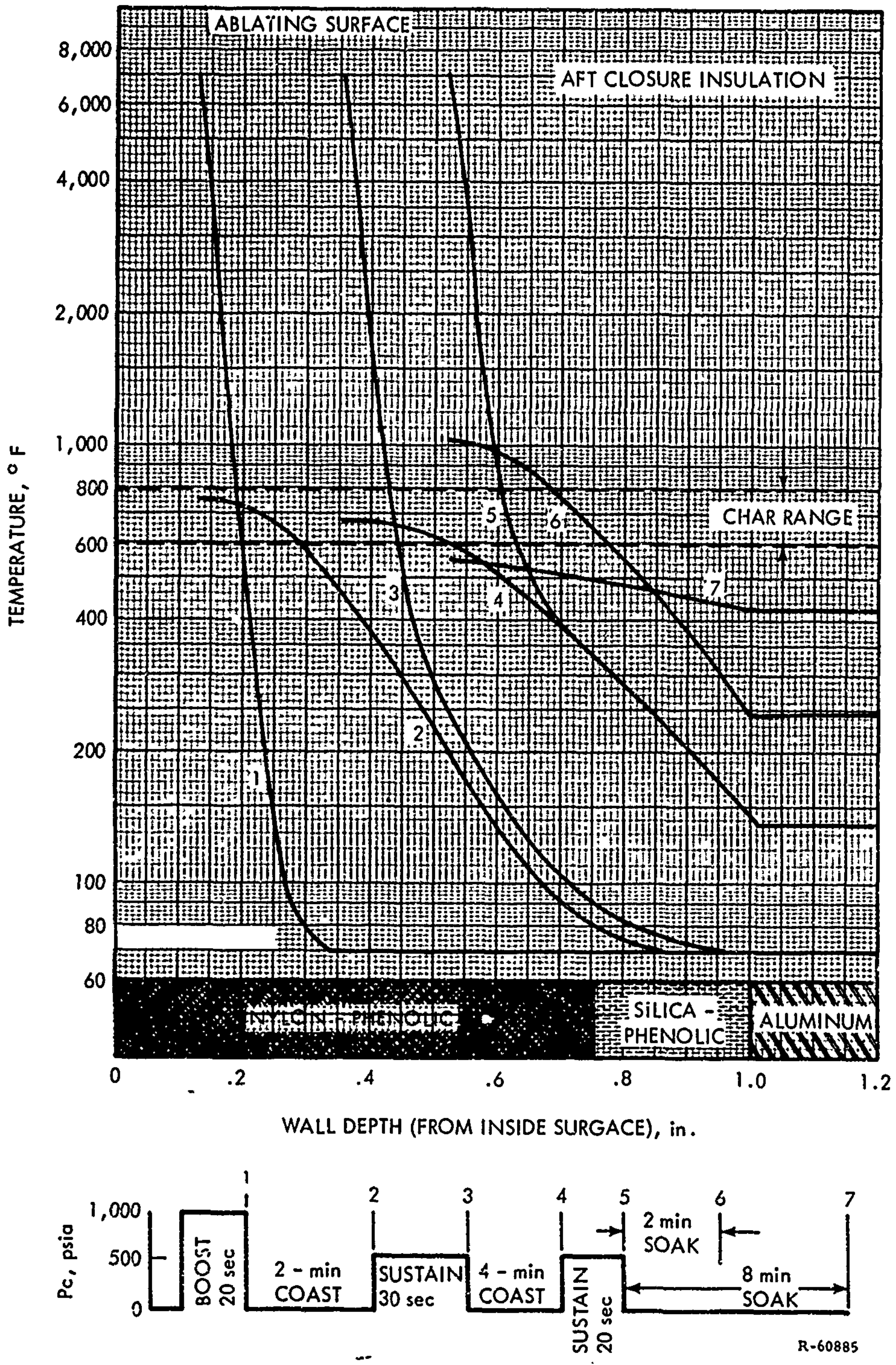


Figure 76. (U) Temperature Profile of Aft Closure Insulation

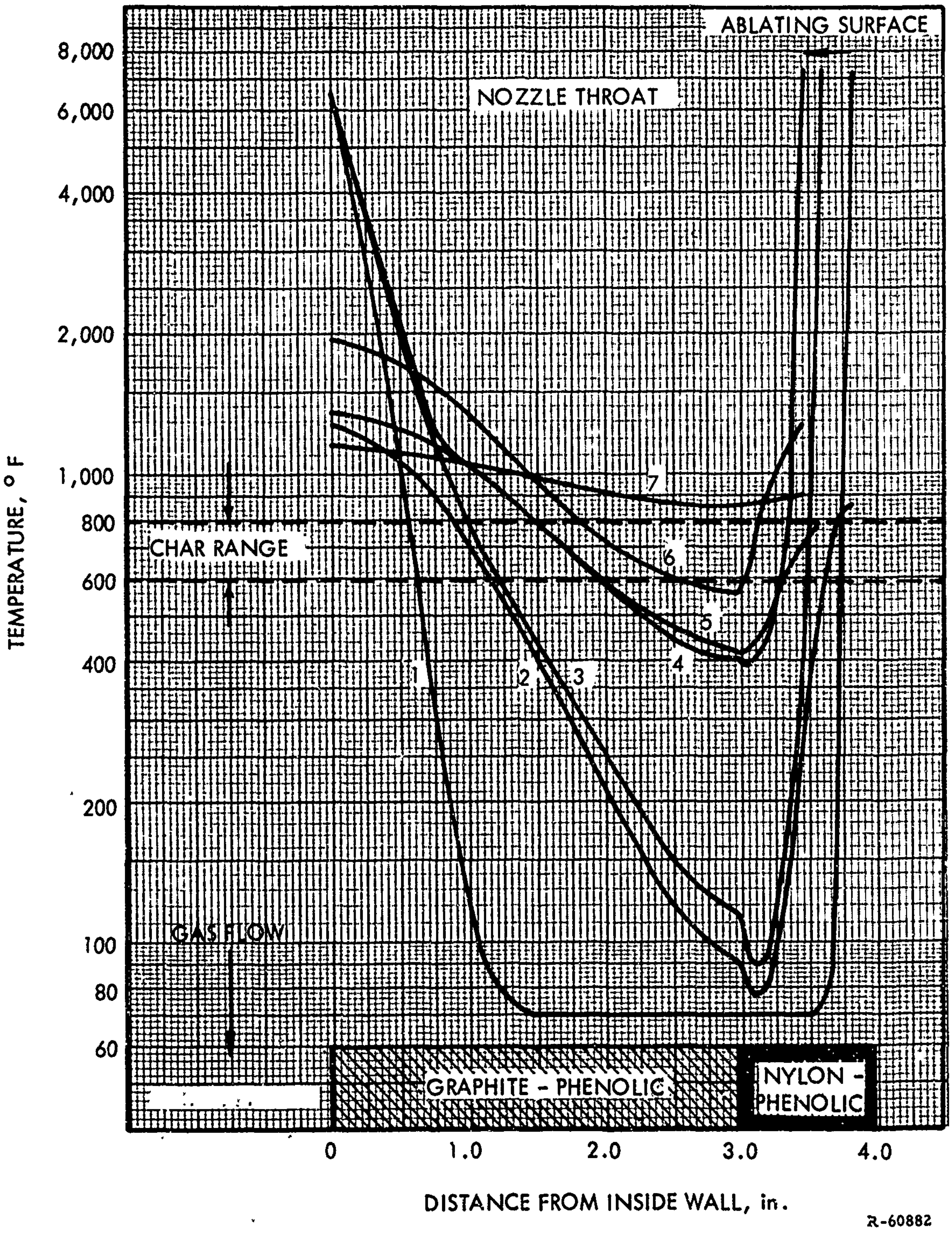


Figure 77. (U) Temperature Profile of Nozzle Throat

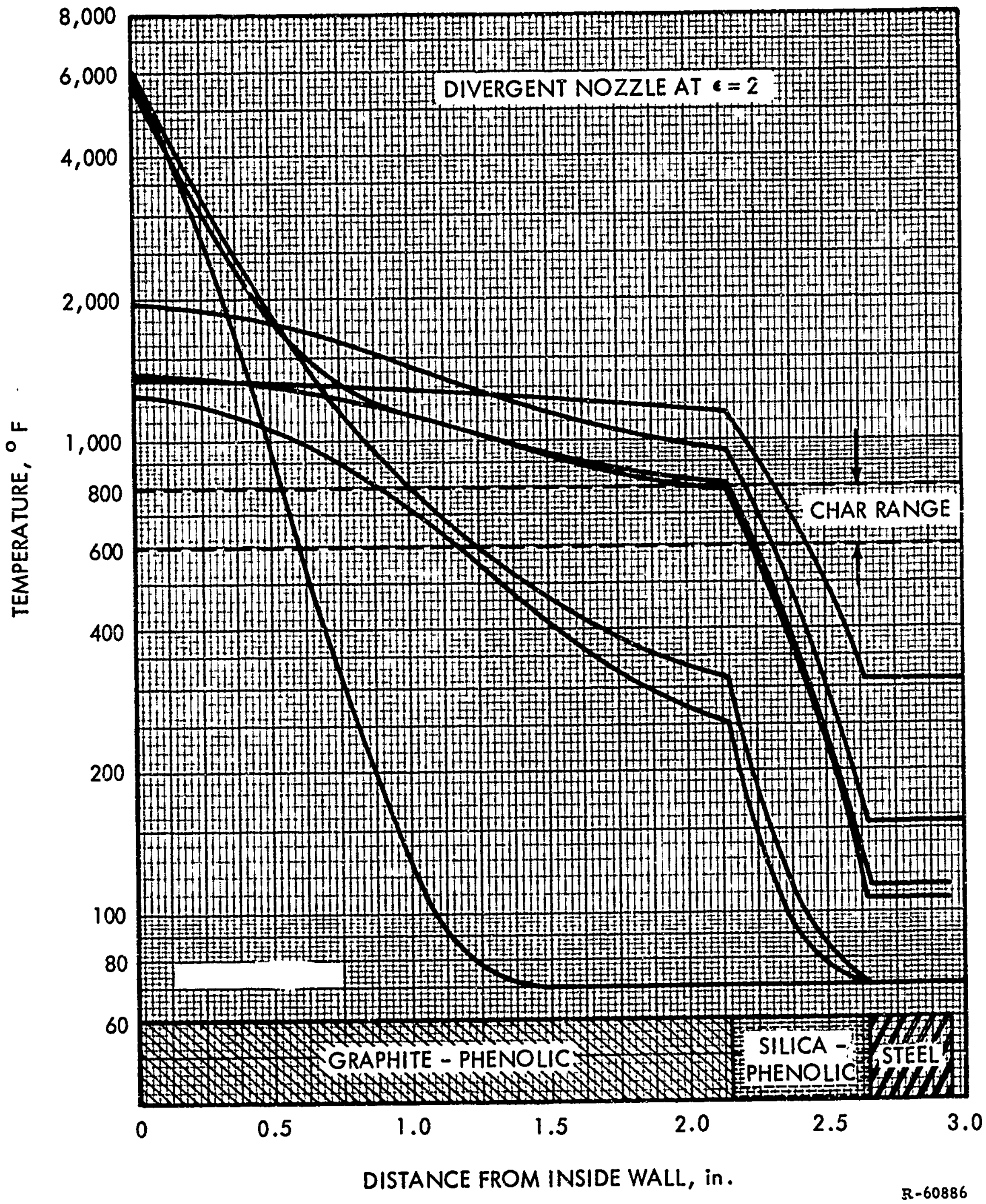


Figure 78. (U) Temperature Profile of Nozzle Skirt

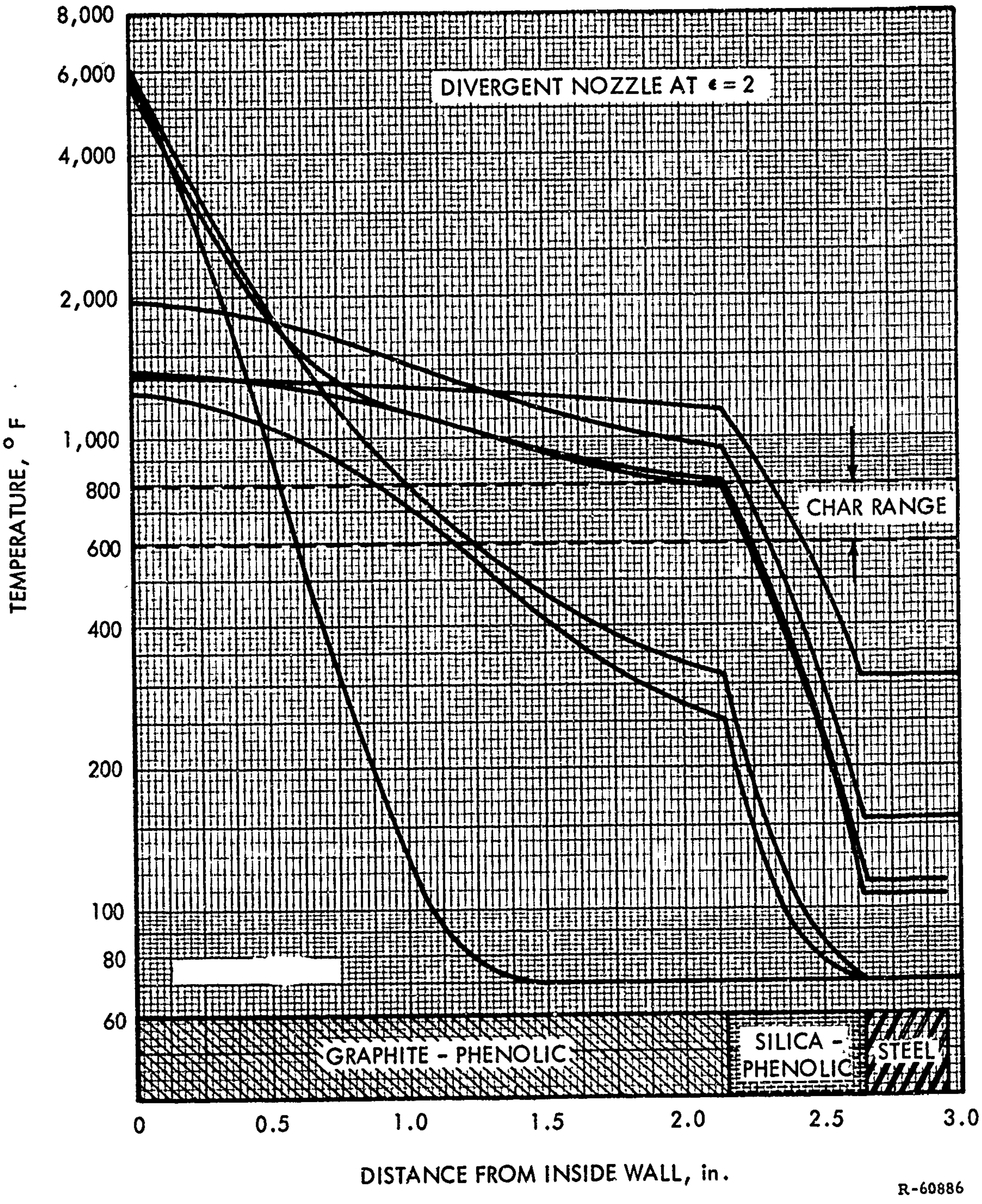


Figure 78. (U) Temperature Profile of Nozzle Skirt

4. MARK II MOTOR TEST

(U) The Mark II thrust chamber configuration (motor No. 007) was tested for 5 sec at a chamber pressure of 1,000 psi in the first test of what was to have been a series of four tests to determine fuel flow rate at the boost thrust level. However, a defective weld on the aft injector failed during ignition and caused the test series to be terminated after 4.8 sec of the 5-sec test. After disassembly the aft closure insulation was sectioned as shown in figure 79. No significant char buildup is present on the inside surface, indicating that the insulation is performing as desired. However, a dimensional stability problem first encountered during closure fabrication is evident, resulting in fracturing of the closure. The nylon-phenolic closure has the tendency to shrink after fabrication. In spite of much care given to the part during cure (careful control of the cure cycle, removal from tool at 325°, 24-hr cooldown period), the part continues to change size and shape.

(U) The thickness of the material (2.0 in.) contributed to the problem. The required thickness was determined from the high erosion rates obtained on Contract NAS 7-311 for the same material. It has since been determined that the higher rates are the results of chemical attack by the fuel system being used on that contract. For future testing, the closure will be modified to include 0.75 in. of buna-N rubber on the outer surface. The reduced nylon-phenolic material thickness is sufficient to survive the extreme duty cycle assumed for thermal analysis.

(U) The Mark II nozzle, shown in figures 80 and 81, appears to be adequate for the duty cycle. The magnesia-phenolic heat shield on the submerged entrance ablated at a rate of approximately 30 mils/sec, while no increase in throat diameter occurred. The postfire throat diameter was approximately 0.050 in. smaller than the prefire diameter, a condition which is normal with ablative throats, but no visible evidence of distortion was noted. The nozzle was not sectioned and will be used on a subsequent test.

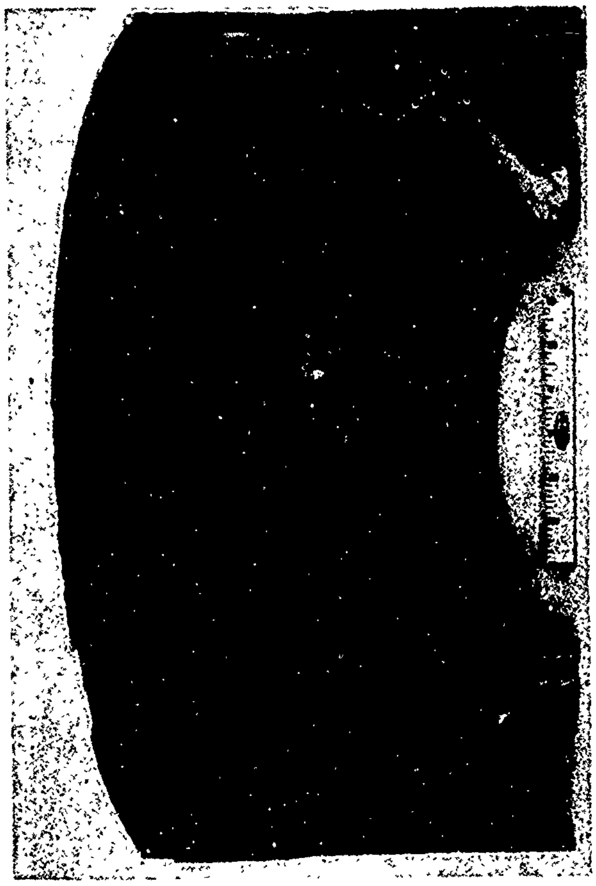


Figure 79. (U) Mark II Configuration Aft Closure Insulation

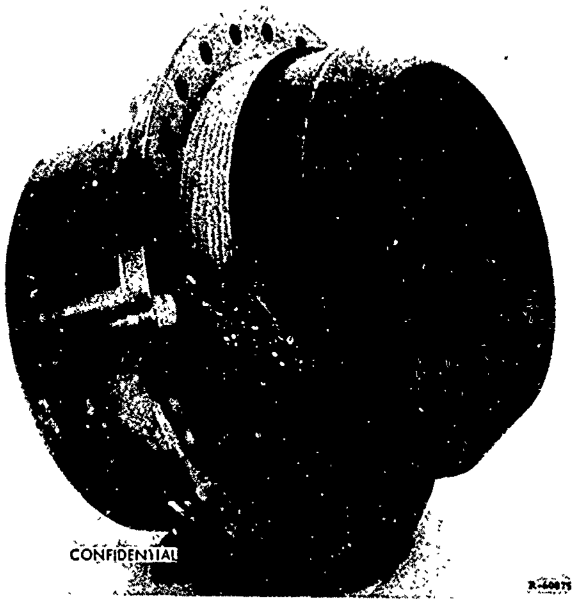


Figure 80. (U) Mark II Configuration Nozzle Assembly

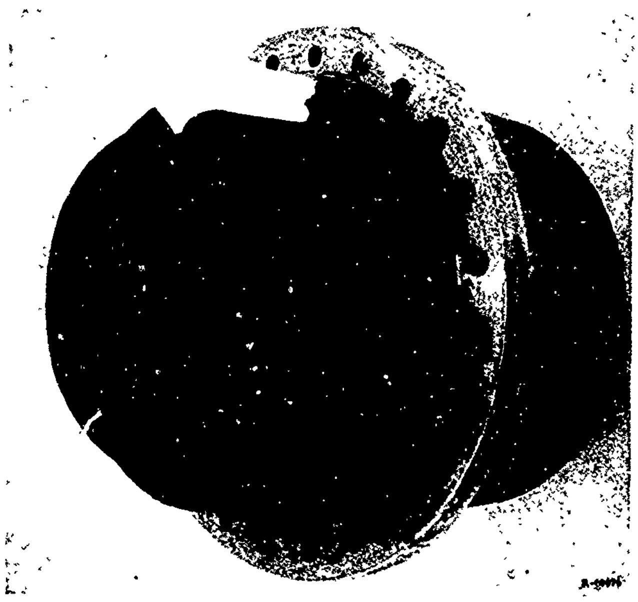


Figure 81. (U) Mark II Configuration
Nozzle Assembly After Test

APPENDIX I

(U) MATERIALS EVALUATION

MATERIALS EVALUATION

(U) Hybrid rocket motors impose a unique motor case insulation problem on the designer in addition to providing harsh nozzle requirements. Hybrid rocket motors require a plenum chamber for mixing oxidizer and fuel vapors which is subjected to extremely high heat loads and to attack by a variety of chemical species. In order to evaluate several materials for application in full-scale motor development for nozzle and plenum materials, a series of ten 5.0-in.-diameter motor tests were conducted with several vendor-supplied material samples. The pertinent motor parameters for these 10 tests are listed in table XVII. The following nozzle and plenum materials were tested.

A. National carbon ATJ graphite

B. Great Lakes Carbon Corp. graphite cloth impregnated with 9.3% carbon-filled hi-char phenolic resin system. (Material designated WBC 8207-1 by manufacturer.)

C. National carbon graphite cloth impregnated with a 7% carbon-filled phenolic resin system (Western Backing Corp., 2242), employing 35% resin solids. (Material designated WCB 8206 by manufacturer.)

D. National carbon graphite cloth impregnated with 8% carbon-filled hi-char resin system (WBC 2223) employing 36% resin solids. (Material designated WBC 8251 by manufacturer.)

E. National carbon graphite cloth impregnated with 10% refractory boride-filled hi-char resin system (WBC 2223). (Material designated as WBC 8218 by the manufacturer.)

F. National carbon cloth impregnated with Evercoat EC221 phenolic design system, employing 7% carbon filler. (Material designated WBC 8221 by manufacturer.)

G. John-Manville Tx magnesium hydroxide paper impregnated with the high-char phenolic resin system (WBC 2223). (Material designated as WBC 7207 by manufacturer.)

H. H. I. Thompson Corporation zirconia paper impregnated with the WBC 2223 high-char phenolic resin system. (Material designated as WBC 7209 by the manufacturer.)

I. United Technology Center's alumina foam, impregnated with Monsanto SC 1008 phenolic resin.

J. A chromic-oxide finished silica cloth (Hitco Irish Refrasil) impregnated with Western Backing Corporation's high-char phenolic resin system (2223) employing 34% resin solids. No filler was used. (Material designated WBC 2234 by manufacturer.)

(U) The materials listed in table XVII were prepared as 2.0-in. inside diameter (ID) orifices for the mixer assembly of a 5.0-in. diameter motor shown in figure 82. The specimens were tested in the 5.0-in.-diameter motor at 300 psi for durations of 10 sec.

(U) After test, the samples were sectioned as shown in figure 83 and char depth and material erosion was measured. The measurements listed in table XVIII are described by figure 84.

(U) Of the test samples, those containing carbon cloth exhibit the greatest resistance to erosion. The best sample being WBC 8207 next to the ATJ graphite control specimen. Samples 2, 3, and 6 exhibit equally low erosion rates with small dimensional change in the internal diameter. The material in sample 4 has been selected for evaluation as a nozzle throat insert material to replace the ATJ graphite insert. The choice was made on the basis of low combined erosion and char depths.

(U) Limited subscale testing is now called for with material samples used as nozzles. Of these samples, all are probably capable of serving at chamber pressures up to 1,000 psi. However, evaluation is now needed at chamber pressures of from 1,000 to 2,000 psi simulating those anticipated in tactical missile systems.

TABLE XVII

(U) 5.0-in.-DIAMETER MOTOR TEST SUMMARY
MATERIALS EVALUATION

Series I

Test No.	Chamber Pressure	Average Thrust	Oxidizer Flow Rate	Burning Time	Sample
L6-0458	276	495	2.01	10.5	Irish refrasil/phenolic
L6-0459	284	507	2.01	10.5	Alumina foam/phenolic
L6-0460	280	531	2.01	10.2	WBC 8206-graphite/phenolic
L6-0461	298	499	2.12	10.6	WBC 8207-graphite/phenolic
L6-0462	298	536	2.12	10.6	WBC 8221-graphite/phenolic
L6-0463	291	543	2.11	10.5	WBC 8207-1-graphite/phenolic
L6-0464	299	556	2.13	10.5	ATJ graphite
L6-0305	276	450	1.95	12.3	WBC 7207-magnesia/phenolic
L6-0304	264	440	1.88	12.3	WBC 7209-zirconia/phenolic
L6-0306	264	445	1.95	12.3	WBC 8218-graphite/phenolic

TABLE XVIII

(U) MATERIALS EVALUATION EROSION AND CHAR DEPTH MEASUREMENTS

Item No.	Material	Radial Erosion in.	Radial Erosion and Char in.	Char in.	Erosion Depth in. a	Erosion Depth in. b	Char in.
1	ATJ Graphite	0.04	—	—	0.09	0.26	—
2	WBC 8208-1	0.09	0.29	0.24	0.19	0.35	0.04
3	WBC 8206	0.01	0.35	0.34	0.17	0.37	0.06
4	WBC 8207	0.05	0.27	0.24	0.16	0.32	0.08
5	WBC 8218	0.08	0.31	0.27	0.22	0.37	0.02
6	WBC 8221	0.01	0.31	0.30	0.20	0.37	0.08
7	Tx Magnesia	0.09	0.07	0.02	0.35	0.58	0.04
8	Zirconia	0.00	0.08	0.08	0.33	0.60	0.04
9	Alumina Foam	0.07	0.07	0.03	0.25	0.51	0.03
10	Irish Refrasil	0.09	0.33	0.28	0.37	0.67	0.04

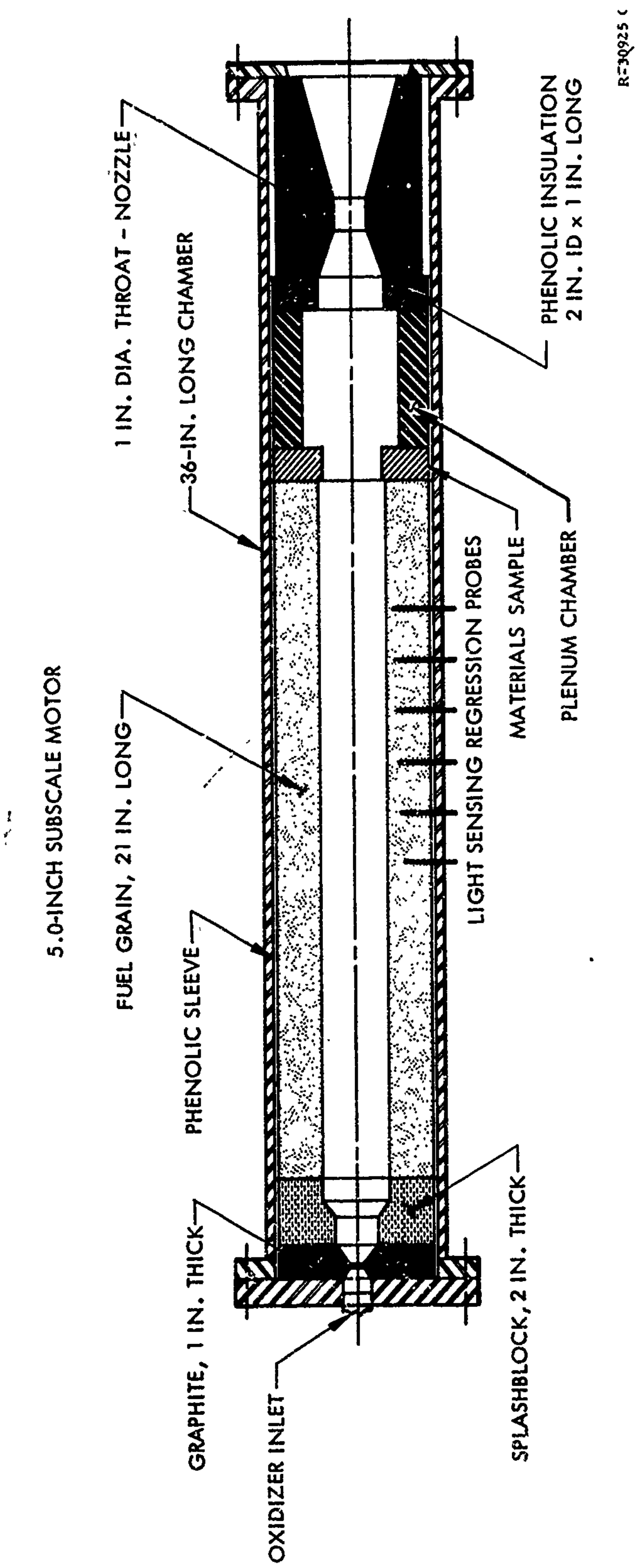


Figure 82. (U) Schematic of 5-in. -Diameter Motor Configuration

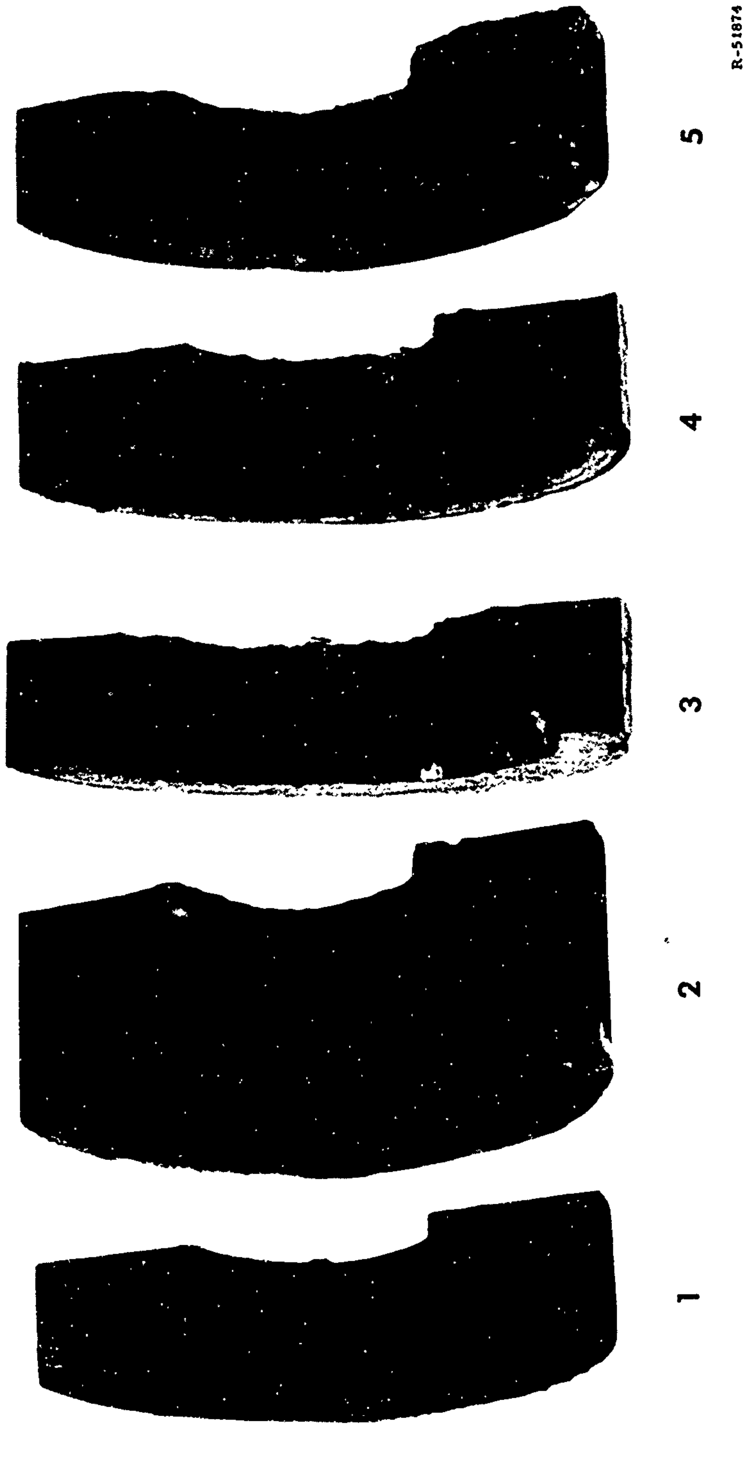


Figure 83. (U) Nozzle and Plenum Material Samples
(Sheet 1 of 2)

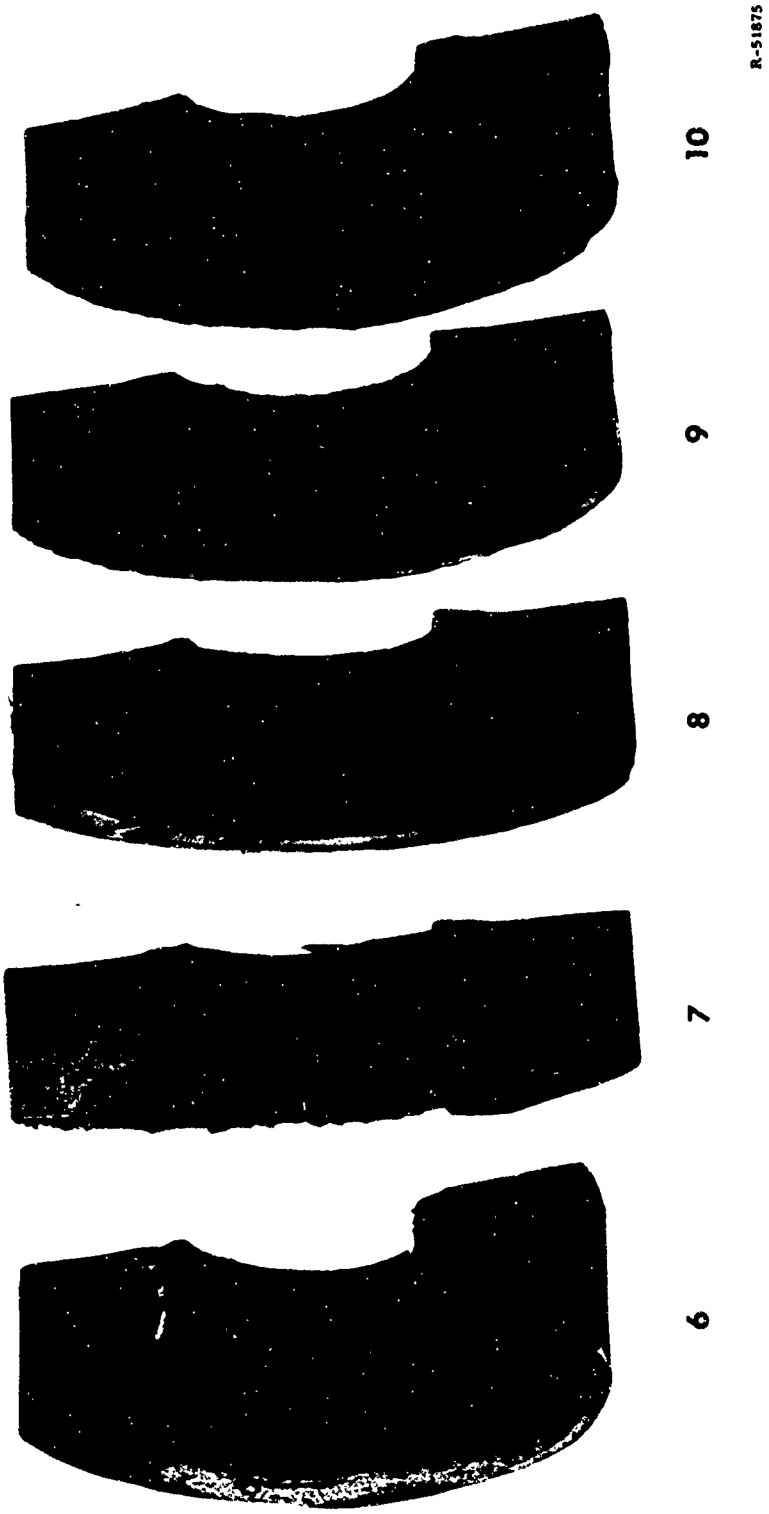


Figure 83. (U) Nozzle and Plenum Material Samples
(Sheet 2 of 2)

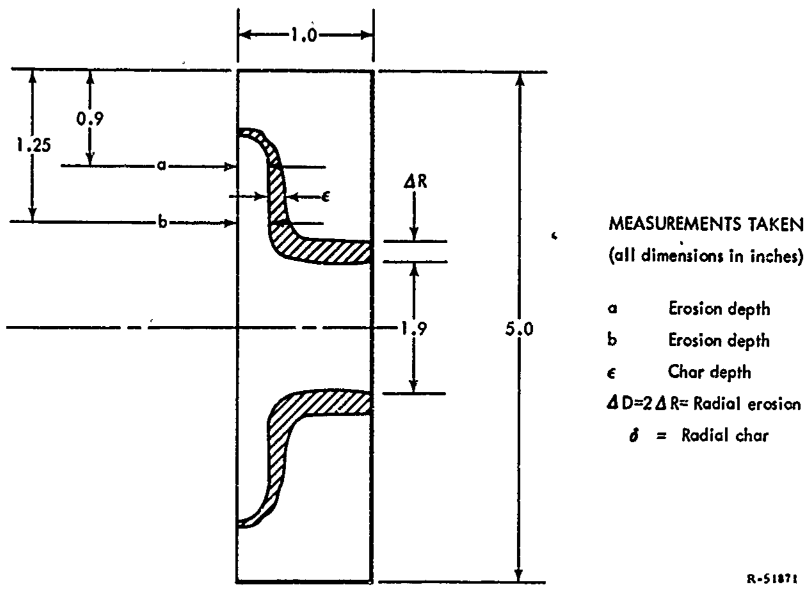


Figure 84. (U) Material Sample Dimensions

APPENDIX II

(U) MOTOR ASSEMBLY DRAWINGS
OF MARK II CONFIGURATION THRUST CHAMBER ASSEMBLY

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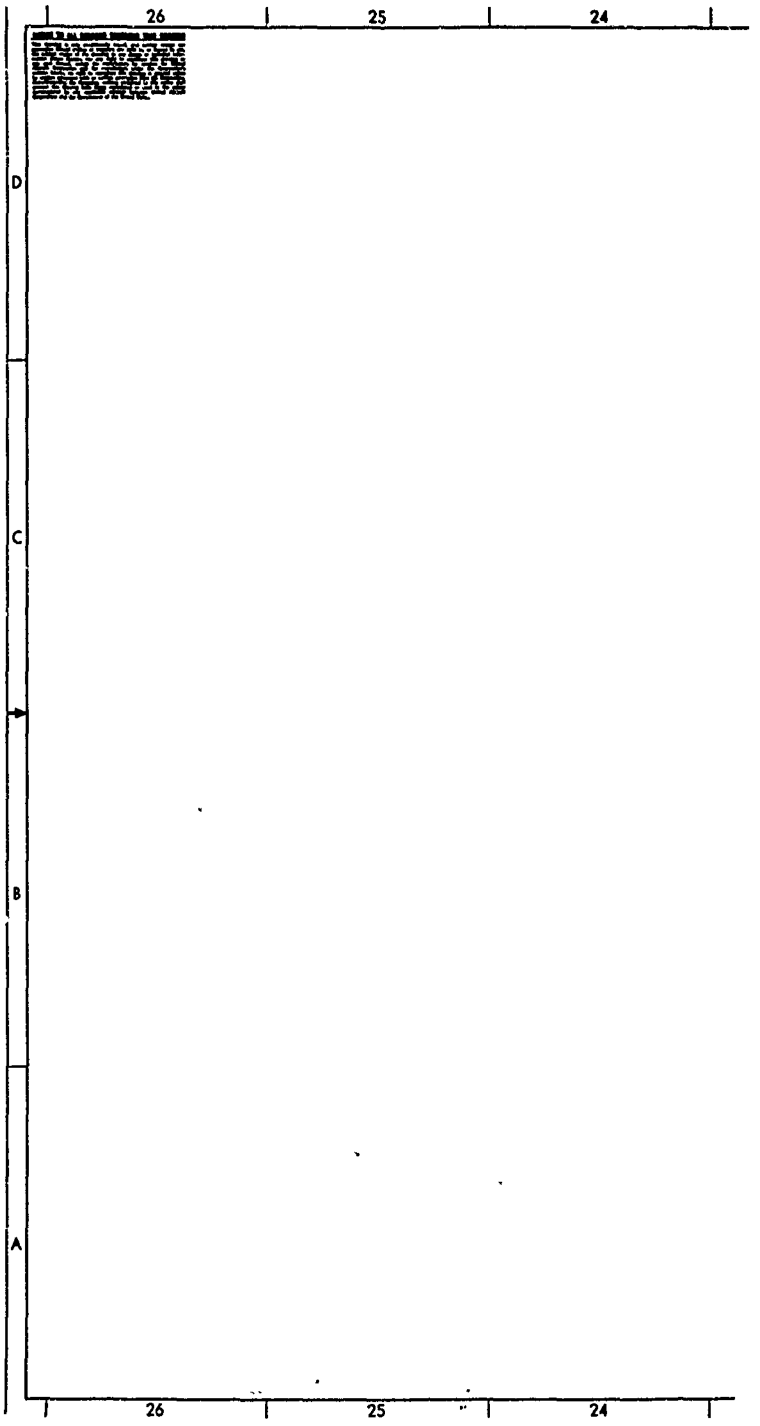

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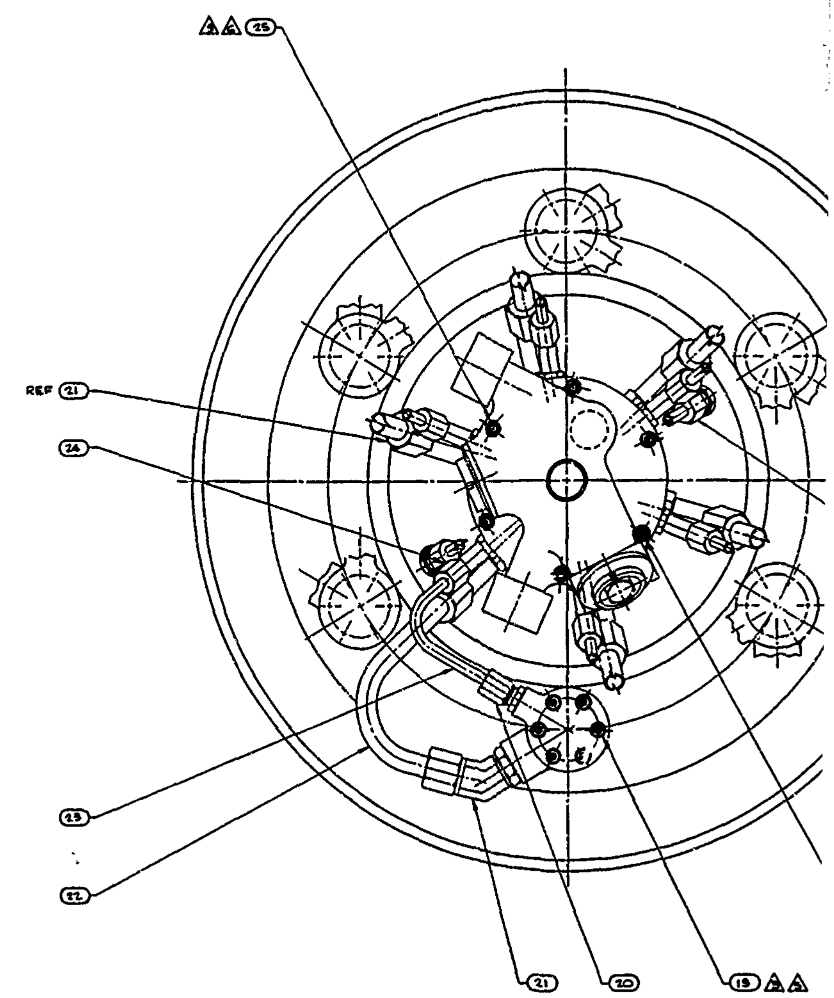

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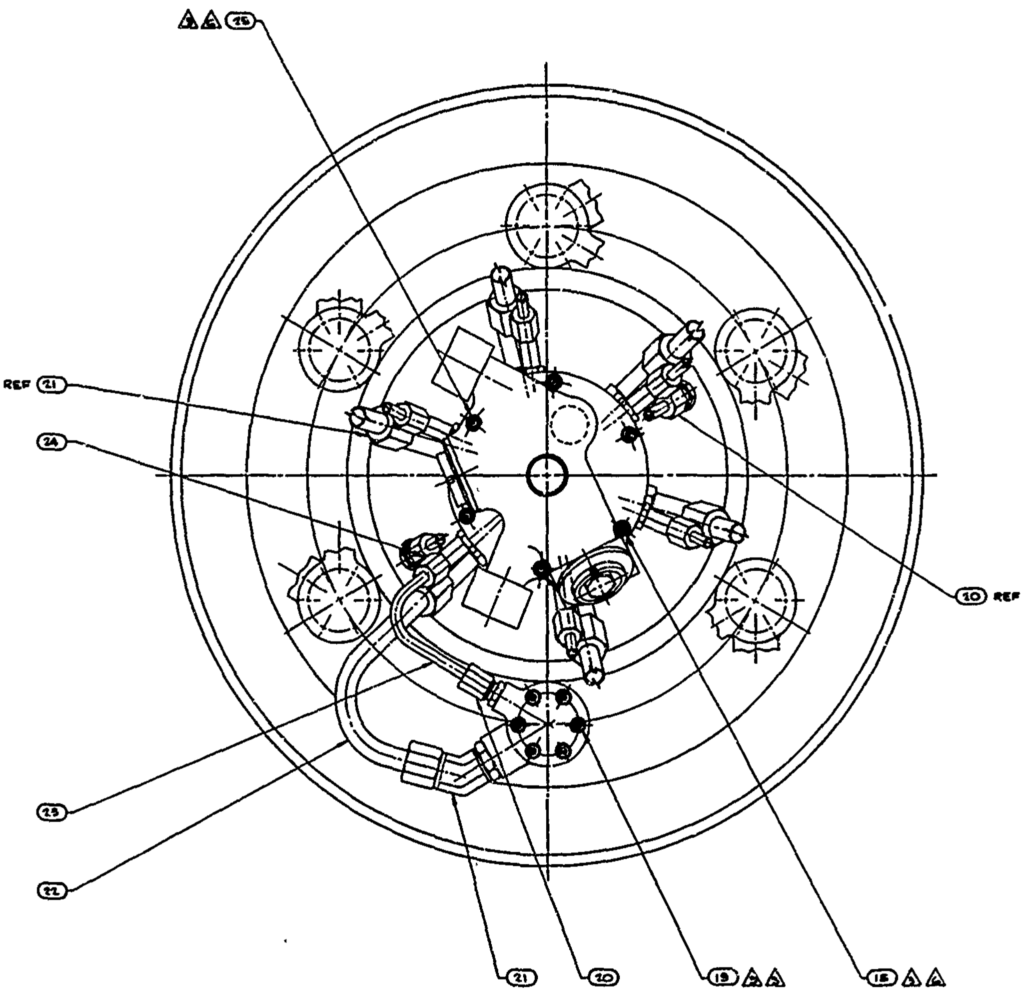

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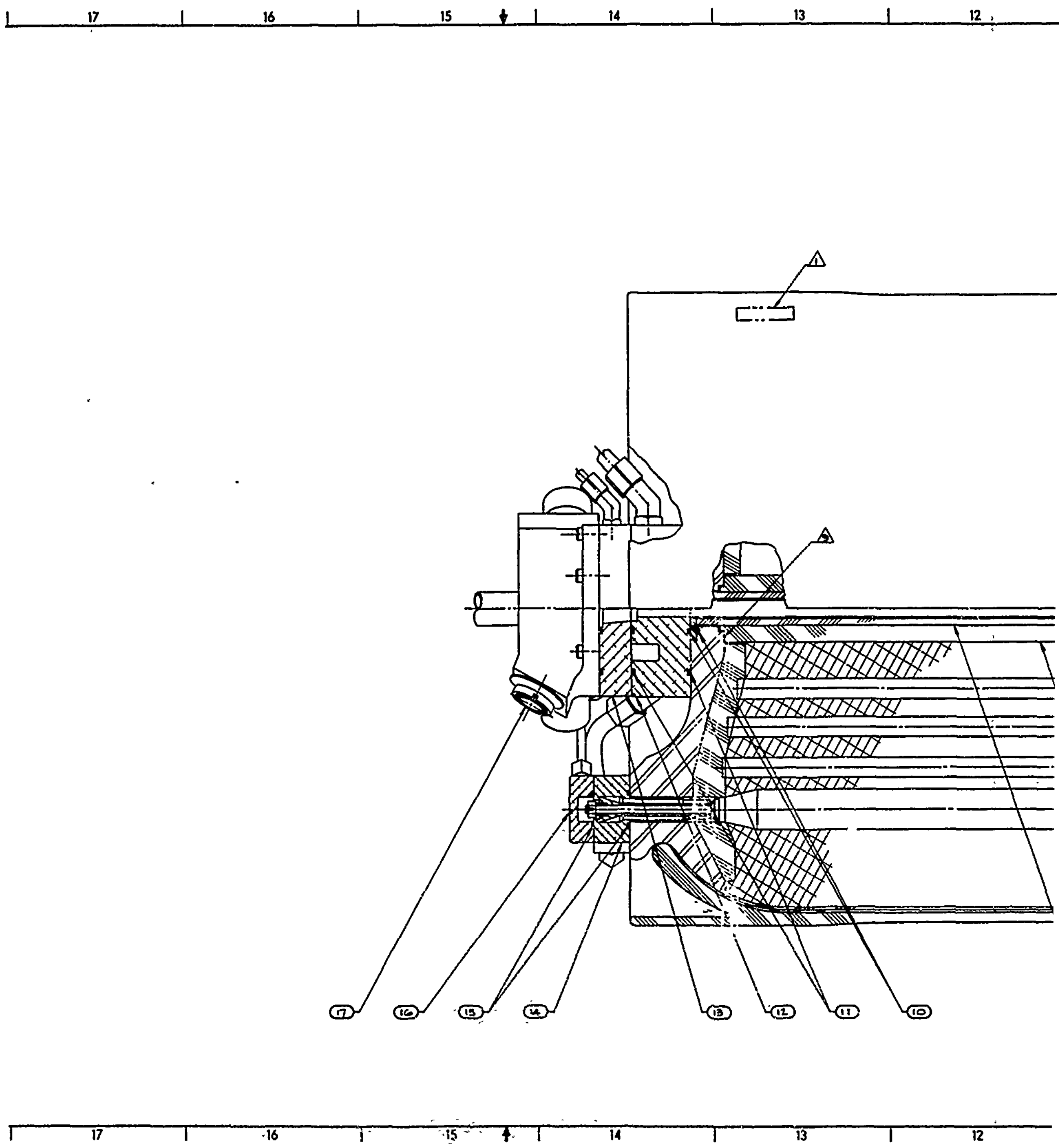

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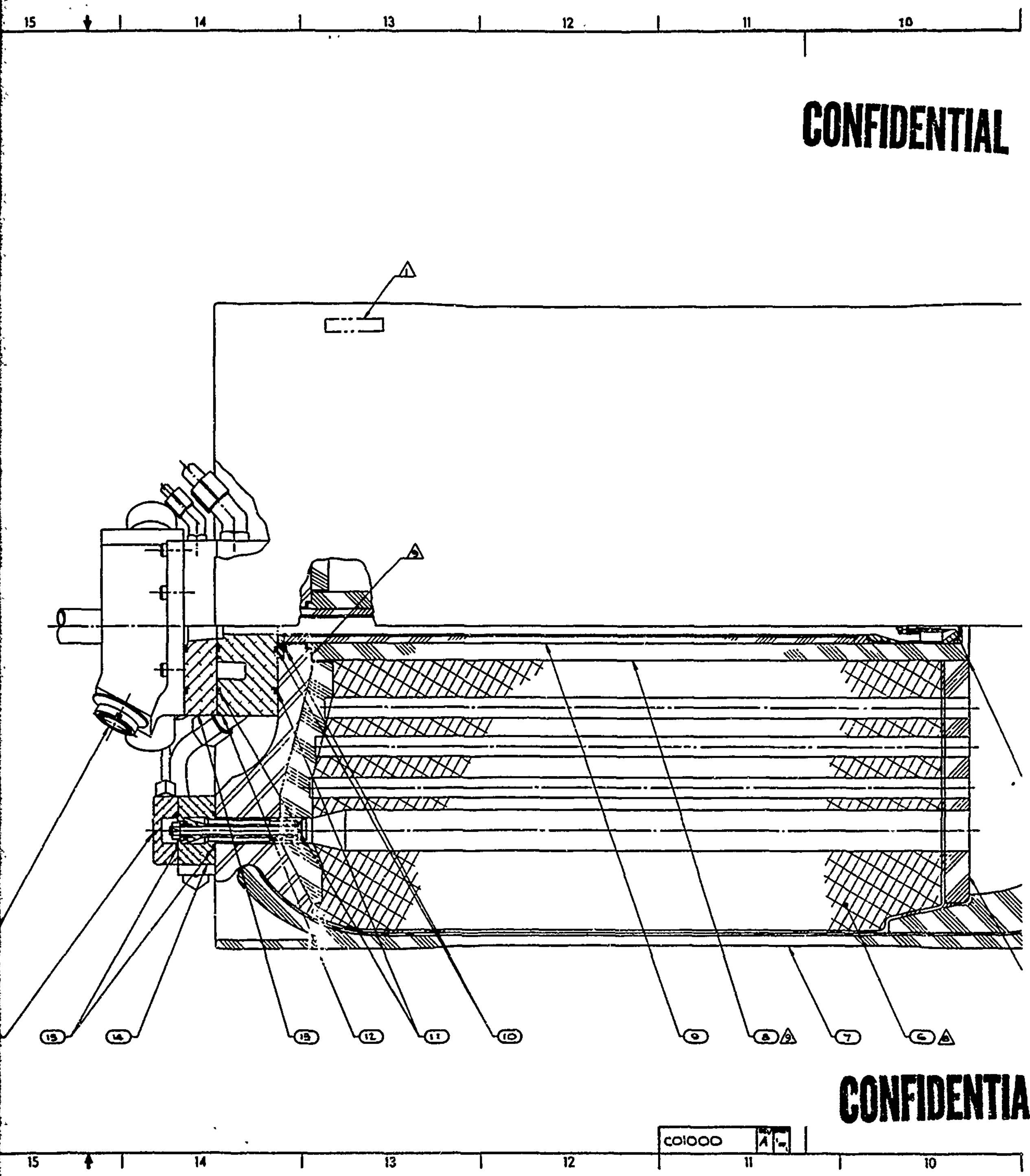

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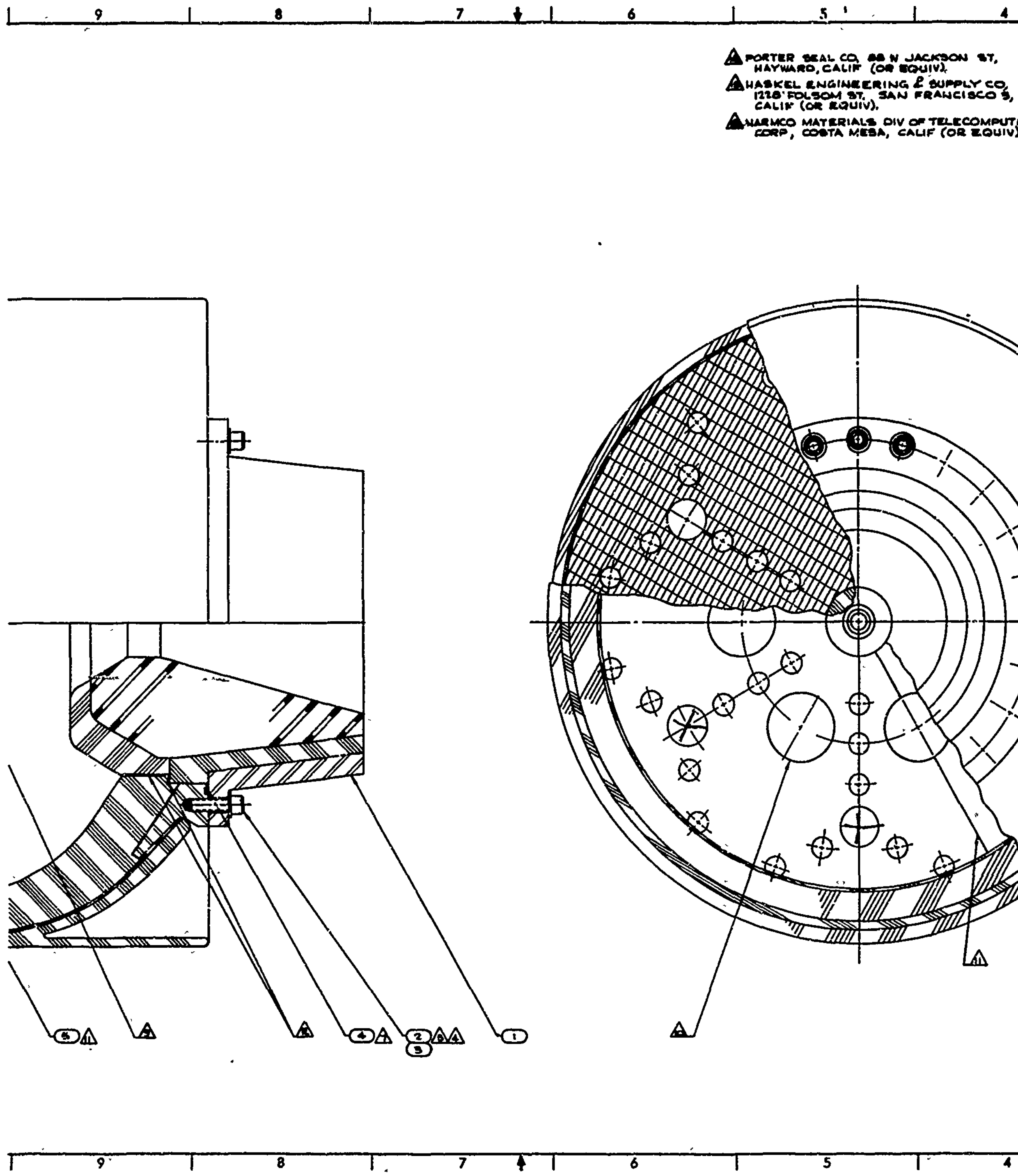
PORTER SEAL CO, 88 N JACKSON ST, HAYWARD, CALIF (OR EQUIV).

HASKEL ENGINEERING & SUPPLY CO, 1228 FOLSOM ST, SAN FRANCISCO 3, CALIF (OR EQUIV).

NARMCO MATERIALS DIV OF TELECOMPUTIN CORP, COSTA MESA, CALIF (OR EQUIV).



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A	W GAN NOTE 9 ADDED C00082. ON FIG. 2041 9/1/10 PICTURE CHANGE		

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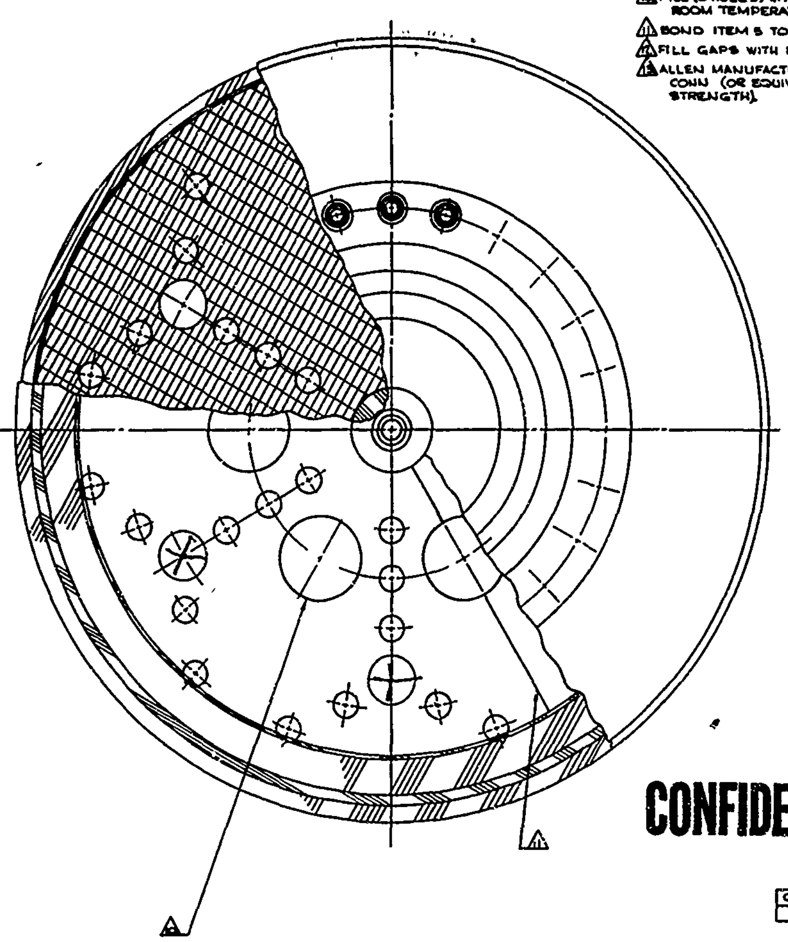
PORTER SEAL CO, 88 N JACKSON ST, HAYWARD, CALIF (OR EQUIV).

HASKEL ENGINEERING & SUPPLY CO, 1228 FOLSOM ST, SAN FRANCISCO 3, CALIF (OR EQUIV).

NARMCO MATERIALS DIV OF TELECOMPUTING CORP, COSTA MESA, CALIF (OR EQUIV).

NOTES:

1. STENCIL PART NO. WITH 1/2 INCH HIGH CHARACTER APPROX AS SHOWN.
2. CHANGES OR SUBSTITUTIONS NOT AFFECTING FUNCTION OF PART MAY BE MADE UPON THE APPROVAL OF THE PROJECT ENGINEER.
3. BOLTS TO BE WELL OILED BEFORE TIGHTING TO INDICATED TORQUE.
4. TORQUE BOLTS TO 50 ± 4 FT LB.
5. TORQUE BOLTS TO 75 ± 10 IN LB.
6. TORQUE BOLTS TO 150 ± 10 IN LB
7. COAT O-RING WITH SILICONE GREASE.
8. PHYSICAL SIZE AND COMPOSITION TO BE SPECIFIED BY COGNIZANT ENGINEER.
9. BOND ITEM 8 TO ITEMS 5 & 7 (INSIDE) WITH ITEM 26 CURE AT 170°-180°F FOR 3 TO 3.2 HOURS.
10. FILL (6 HOLES) WITH ITEM 27 AND CURE AT ROOM TEMPERATURE FOR 8 HOURS.
11. BOND ITEM 5 TOGETHER USING ITEM 26.
12. FILL GAPS WITH ITEM 28.
13. ALLEN MANUFACTURING CO, HARTFORD 1, CONN (OR EQUIV 160,000 PSI MIN TENSILE STRENGTH).



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C01000-01-01
PART NO.

Note	Qty	Part No.	Description	Zone	Item
12	AR	—	ZINC CHROMATE PUTTY	/	28
10, 12	AR	—	NARMCO 4056	/	27
11, 12	AR	—	METLBOND 316 ADHESIVE	/	26
	2	NS20004-64	BOLT- INTERNAL WRENCHING 3.750 LG	[illegible]	25
15	6	4W58U-55	STRAIGHT THD 45° ELBOW FERULOK TEFLON O-RING (PARKER)	[illegible]	24
	6	C01073-01-01	TUBE, MANIFOLD, SUSTAIN	[illegible]	23
	6	C01074-01-01	TUBE, MANIFOLD, BOOST	[illegible]	22
15	12	4W58U-55	STRAIGHT THD 45° ELBOW FERULOK TEFLON O-RING (PARKER)	[illegible]	21
15	8	4F58U-55	STRAIGHT THD CONNECTOR FERULOK TEFLON O-RING (PARKER)	[illegible]	20
	50	—	SOC HD CAP SCR - STL NO. 10-32 UNF-3A × .175 LG	[illegible]	19
	4	NS20004-52	BOLT- INTERNAL WRENCHING 3.750 LG	[illegible]	18
	1	—	VALVE-OXIDIZER	[illegible]	17
	6	C01072-01-01	CAP, MANIFOLD, SUSTAIN	[illegible]	16
16	12	2-119	O-RING, COMPOUND TEFLON (PARKER)	[illegible]	15
	6	C01075-01-01	INJECTOR, FWD, DUAL ORIFICE POPPET	[illegible]	14
	1	C01070-01-01	MANIFOLD, SUSTAIN	[illegible]	13
	1	C01071-01-01	MANIFOLD, BOOST	[illegible]	12
14	3	2-154	O-RING, COMPOUND TEFLON (PARKER)	[illegible]	11
14	4	2-125	O-RING, COMPOUND TEFLON (PARKER)	[illegible]	10
	1	C01086-01-01	INJECTOR, POPPET, AFT	11/A	9
	1	C01020-01-01	AFT INJECTOR TUBE	11/A	8
	1	C01252-01-01	CASE	[illegible]	7
8	AR	—	FUEL GRAIN	[illegible]	6
11	1	C01104-01-01	AFT GRAIN INSULATION	9/A	5
14	1	2-273	O-RING, COMPOUND NO. 77-545 (PARKER)	[illegible]	4
	24	—	WASHER, PLAIN - STL FOR 5/8 DIA BOLT 5/4 O.D.	7/A	3
	24	—	CAP SCREW, SOCKET HD, STL 5/8-24 UNF-3A × 1.25 LG	7/A	2
	1	C00990-01-01	NOZZLE ASSY	7/A	1

United Technology Center

MOTOR ASSEMBLY, MK II, MOD 2- 15 FILAMENT WOUND HYBRID MOTOR

14134 J C01000 A

C01000 A

DWG NO. 3516

155/156

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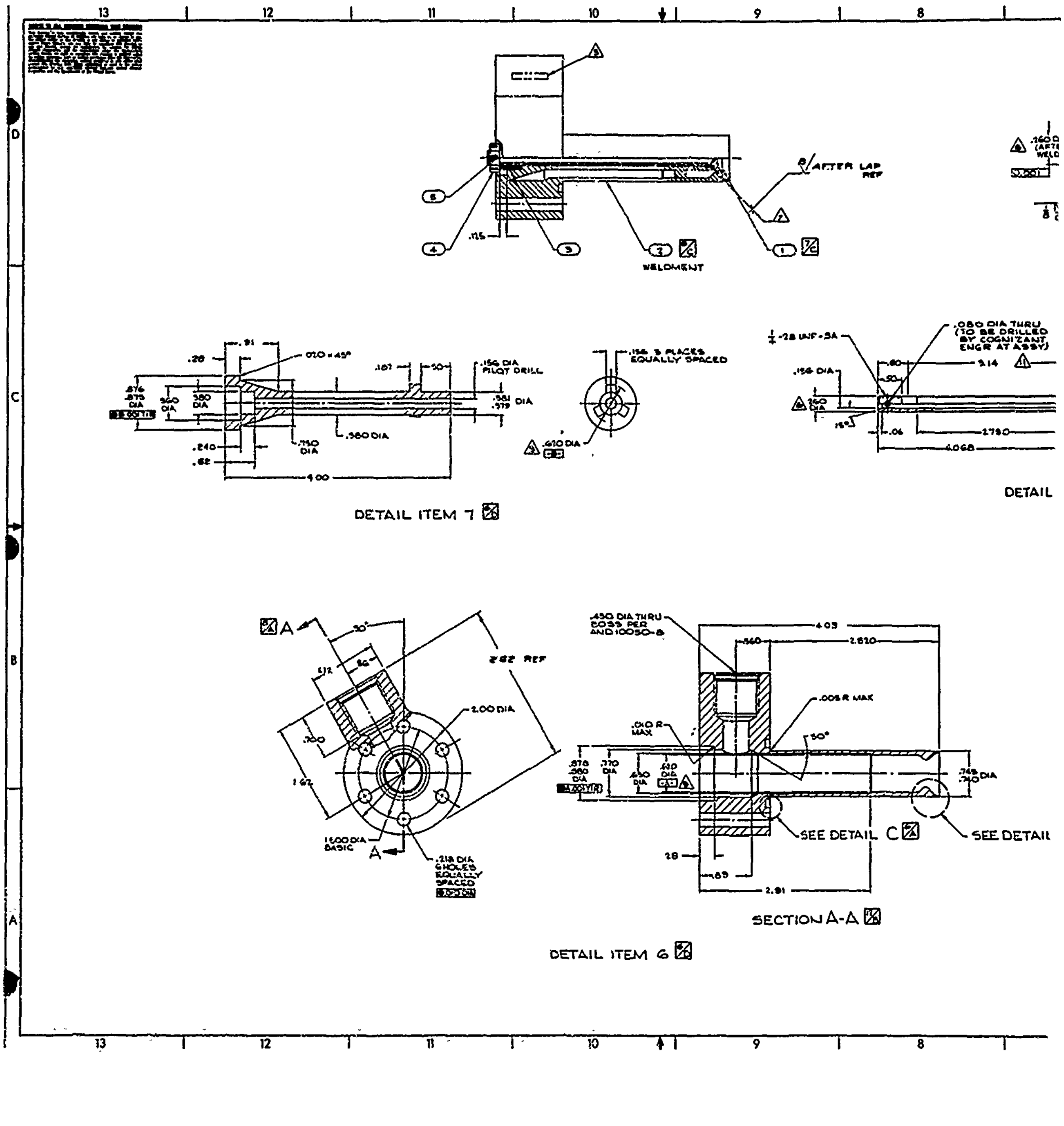

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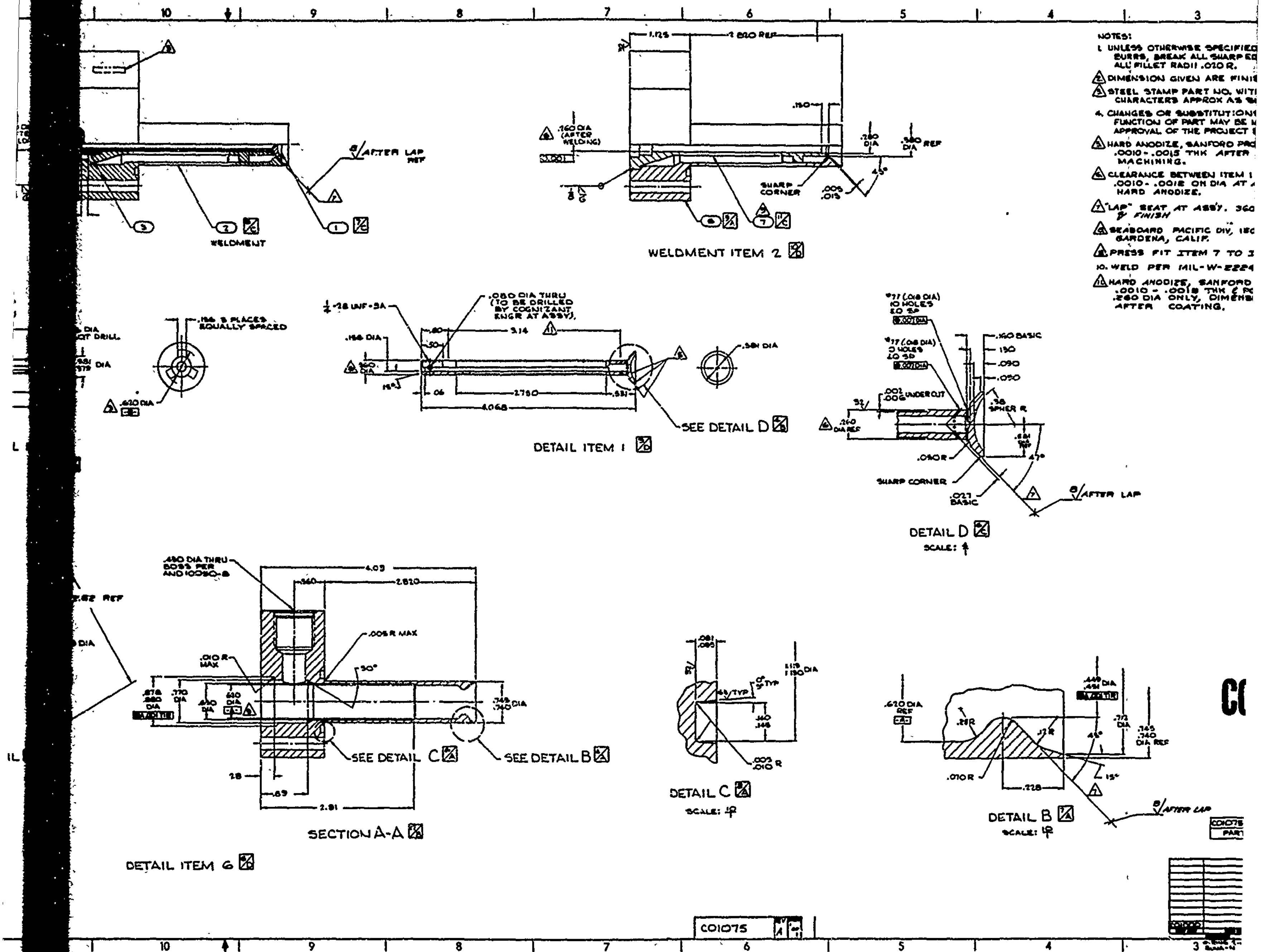

NOTES:
1. UNLESS OTHERWISE SPECIFIED
ALL FILLET RADII .010 R.
WELDMENT
WELDMENT ITEM 2
DETAIL ITEM 1
SEE DETAIL D
DETAIL D
SCALE: 4
SECTION A-A
SEE DETAIL C
SEE DETAIL B
DETAIL C
DETAIL B
DETAIL ITEM 6
SHARP CORNER
C01075

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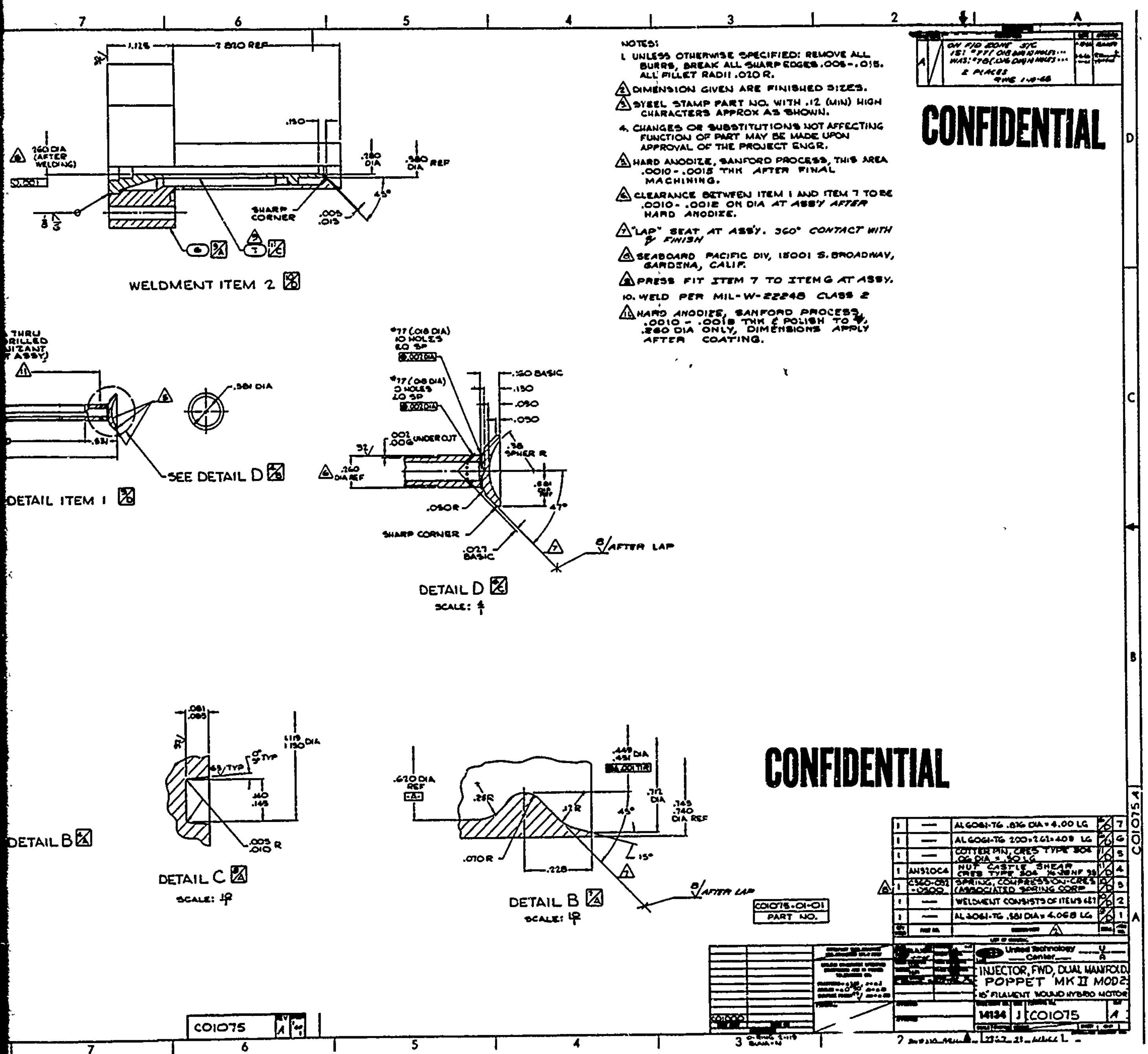

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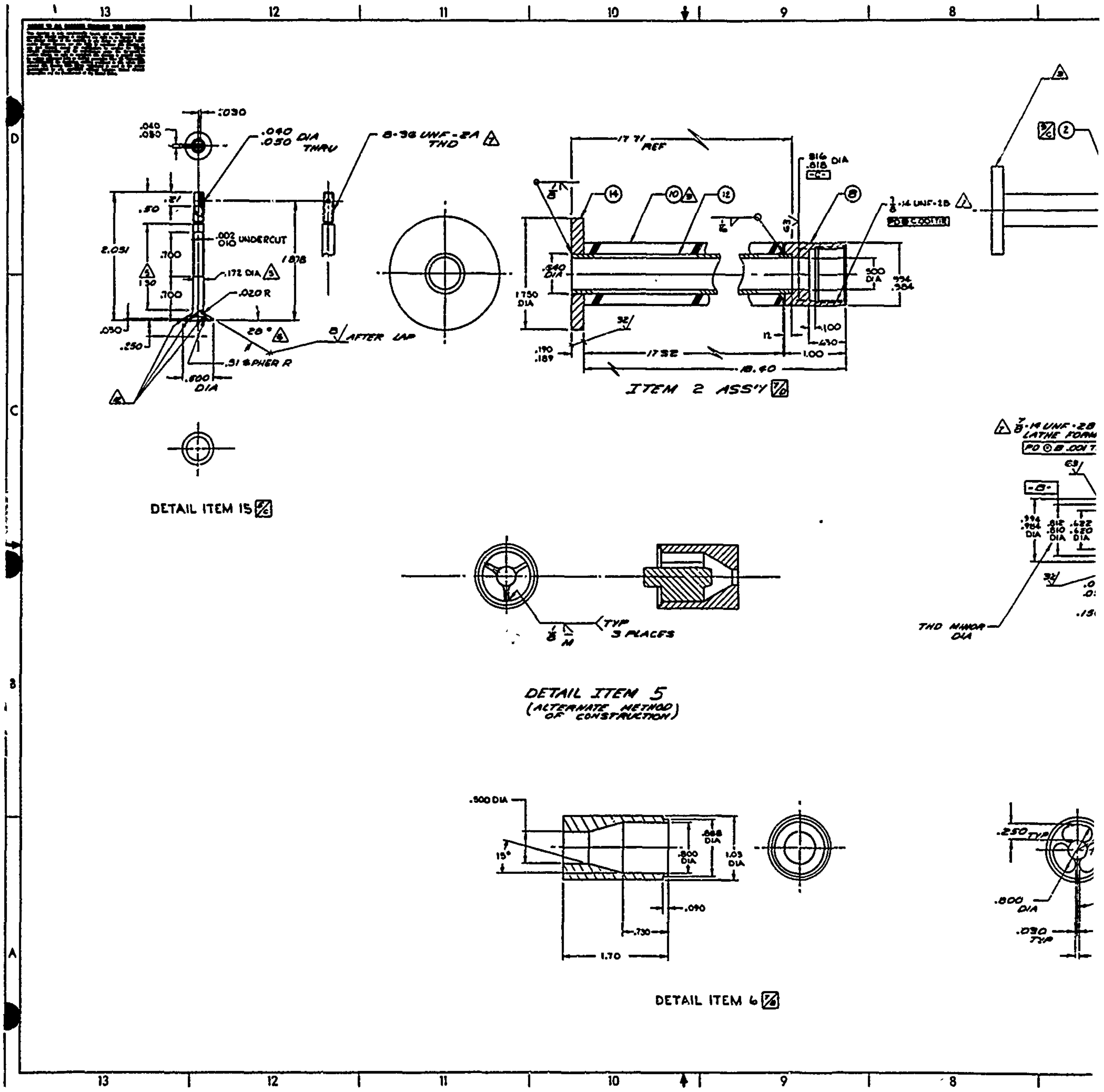

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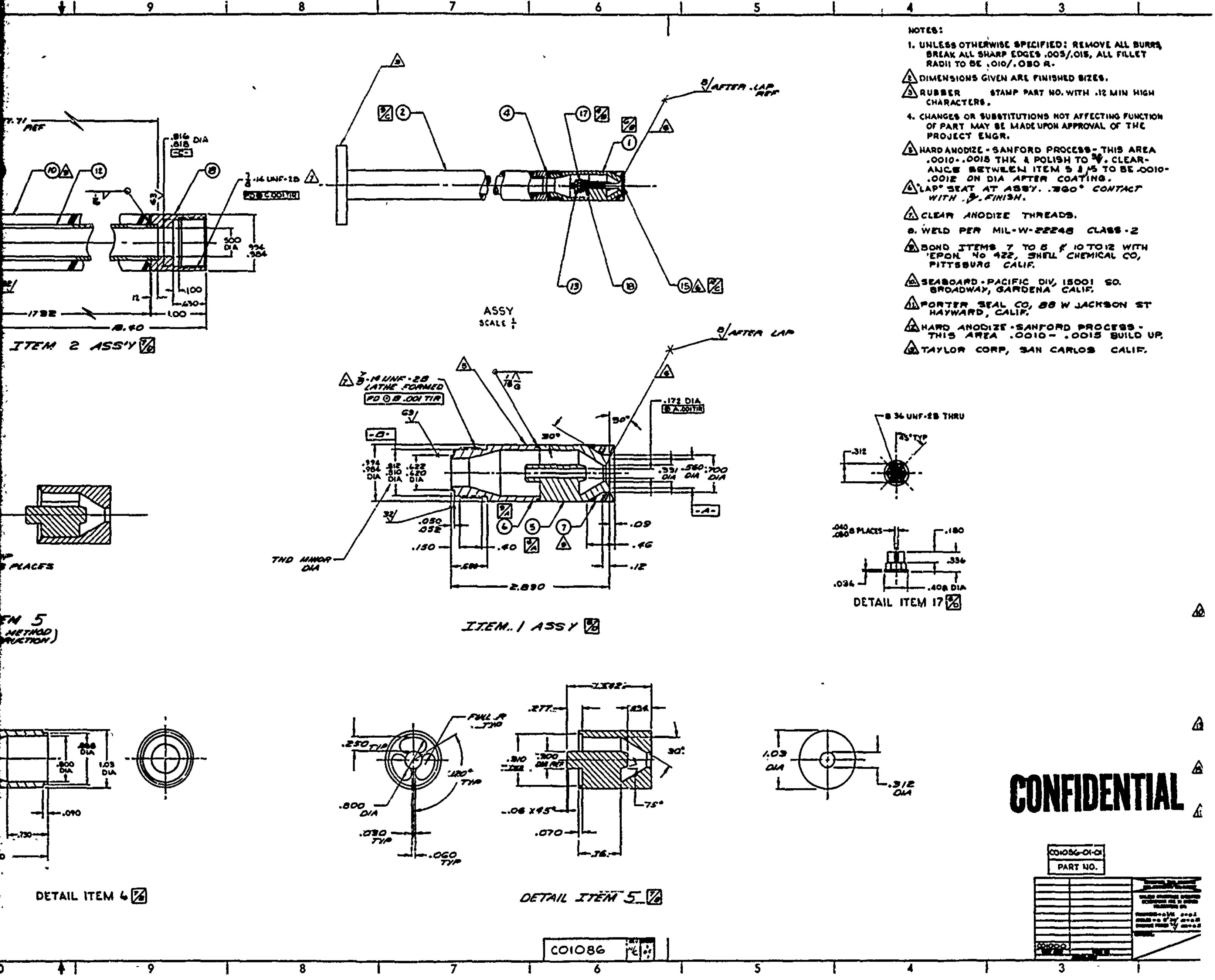

NOTES:

1. UNLESS OTHERWISE SPECIFIED: REMOVE ALL BURRS, BREAK ALL SHARP EDGES .005/.015, ALL FILLET RADII TO BE .010/.030 R.
2. DIMENSIONS GIVEN ARE FINISHED SIZES.
3. RUBBER STAMP PART NO. WITH .12 MIN HIGH CHARACTERS.
4. CHANGES OR SUBSTITUTIONS NOT AFFECTING FUNCTION OF PART MAY BE MADE UPON APPROVAL OF THE PROJECT ENGR.
5. HARD ANODIZE - SANFORD PROCESS - THIS AREA .0010-.0018 THK & POLISH TO 8. CLEARANCE BETWEEN ITEM 5 & 15 TO BE .0010-.0012 ON DIA AFTER COATING.
6. "LAP" SEAT AT ASS'Y. 360° CONTACT WITH 8 FINISH.
7. CLEAR ANODIZE THREADS.
8. WELD PER MIL-W-22248 CLASS-2
9. BOND ITEMS 7 TO 8 & 10 TO 12 WITH 'EPON No 422, SHELL CHEMICAL CO, PITTSBURG CALIF.
10. SEABOARD-PACIFIC DIV, 15001 SO. BROADWAY, GARDENA CALIF.
11. PORTER SEAL CO, 88 W JACKSON ST HAYWARD, CALIF.
12. HARD ANODIZE - SANFORD PROCESS - THIS AREA .0010 - .0015 BUILD UP.
13. TAYLOR CORP, SAN CARLOS CALIF.

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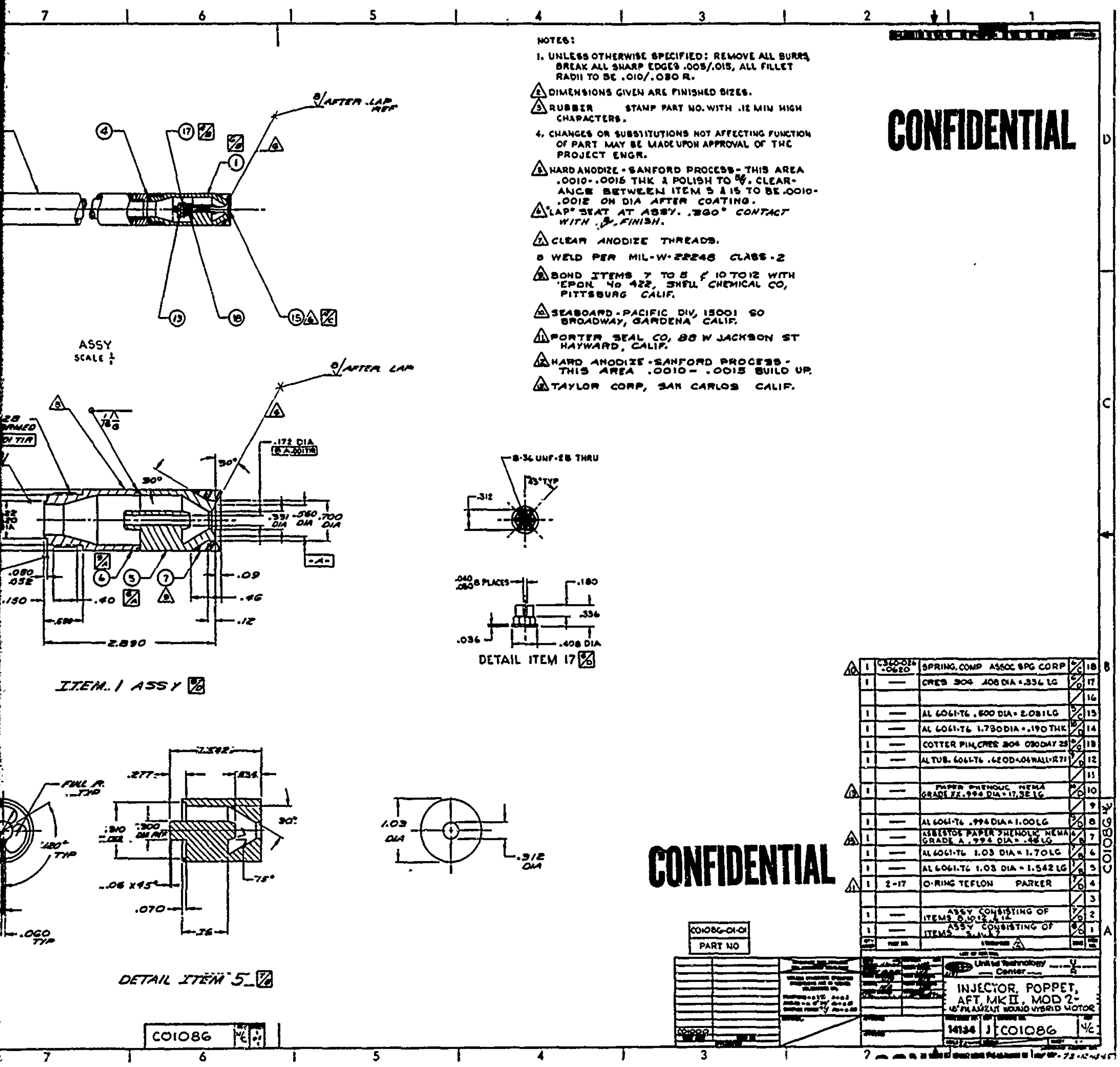
NOTES:
1. UNLESS OTHERWISE SPECIFIED: REMOVE ALL BURRS, BREAK ALL SHARP EDGES .005/.015, ALL FILLET RADII TO BE .010/.030 R.
2 DIMENSIONS GIVEN ARE FINISHED SIZES.
3 RUBBER STAMP PART NO. WITH .12 MIN HIGH CHARACTERS.
4. CHANGES OR SUBSTITUTIONS NOT AFFECTING FUNCTION OF PART MAY BE MADE UPON APPROVAL OF THE PROJECT ENGR.
5 HARD ANODIZE - SANFORD PROCESS - THIS AREA .0010-.0015 THK & POLISH TO 16. CLEARANCE BETWEEN ITEM 5 & 15 TO BE .0010-.0012 ON DIA AFTER COATING.
6 "LAP" SEAT AT ASSY. 360° CONTACT WITH 8 FINISH.
7 CLEAR ANODIZE THREADS.
8 WELD PER MIL-W-22248 CLASS-2
9 BOND ITEMS 7 TO 5 & 10 TO 12 WITH 'EPON' No 422, SHELL CHEMICAL CO, PITTSBURG CALIF.
10 SEABOARD-PACIFIC DIV, 15001 SO BROADWAY, GARDENA CALIF.
11 PORTER SEAL CO, 88 W JACKSON ST HAYWARD, CALIF.
12 HARD ANODIZE - SANFORD PROCESS - THIS AREA .0010 - .0015 BUILD UP.
13 TAYLOR CORP, SAN CARLOS CALIF.
CONFIDENTIAL
ASSY
SCALE 1/1
8/AFTER LAP REF
8/AFTER LAP
ITEM 1 ASSY
DETAIL ITEM 17
DETAIL ITEM 5
8-36 UNF-2B THRU
1 | C360-026-.0620 | SPRING, COMP ASSOC SPG CORP | 18
1 | — | CRES 304 .408 DIA x .336 LG | 17
16
1 | — | AL 6061-T6 .500 DIA x 2.081 LG | 15
1 | — | AL 6061-T6 1.750 DIA x .190 THK | 14
1 | — | COTTER PIN, CRES 304 .030 DIA | 13
1 | — | AL TUB. 6061-T6 .62 OD x .04 WALL | 12
11
1 | — | PAPER PHENOLIC NEMA GRADE XX .994 DIA x 17.32 LG | 10
9
1 | — | AL 6061-T6 .994 DIA x 1.00 LG | 8
1 | — | ASBESTOS PAPER PHENOLIC NEMA GRADE A .994 DIA x .46 LG | 7
1 | — | AL 6061-T6 1.03 DIA x 1.70 LG | 6
1 | — | AL 6061-T6 1.03 DIA x 1.542 LG | 5
1 | 2-17 | O-RING TEFLON PARKER | 4
3
1 | — | ASSY CONSISTING OF ITEMS 8, 10, 12, & 14 | 2
1 | — | ASSY CONSISTING OF ITEMS 5, ... 17 | 1
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PART NO
United Technology Center
INJECTOR, POPPET, AFT, MK II, MOD 2-
48" FILAMENT WOUND HYBRID MOTOR
14134 | J | C01086
C01086

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9 MOLD AT 310°-325°F, 1000 PSI FOR 2 HOURS AND BOND TO ITEMS 2 AND 3 WITH ITEM 5.

10 PREPARE MATING SURFACE BETWEEN ITEMS 2 & 4 AS FOLLOWS:

a. DEGREASE
b. ETCH FOR 2 MINUTES (MIN) AT 180°F WITH A SOLUTION OF 841 ml 35 % HYDROCHLORIC ACID, 89 ml 85% PHOSPHORIC ACID AND 43 ml OF 60% HYDROFLUORIC ACID.
c. RINSE WITH DISTILLED WATER.
d. FORCE AIR DRY FOR 30 MINUTES (MIN).

11 BOND ITEM 2 TO ITEM 4 USING ITEM 6. ALTERNATE FOR ITEM 6, ADHESIVE, EPON NO. 422 SHELL CHEMICAL CO, PITTSBURG CALIF.

12 NARMCO MATERIALS DIV OF TELE COMPUTING CORP, COSTA MESA, CALIF

NOTES:

1. UNLESS OTHERWISE SPECIFIE[D]
BURRS, BREAK ALL SHARP E[DGES]
ALL FILLET RADII .020R.

2 DIMENSIONS GIVEN ARE FINIS[H]

3 RUBBER STAMP PART NO. WITH
CHARACTERS APPROX AS S[HOWN]

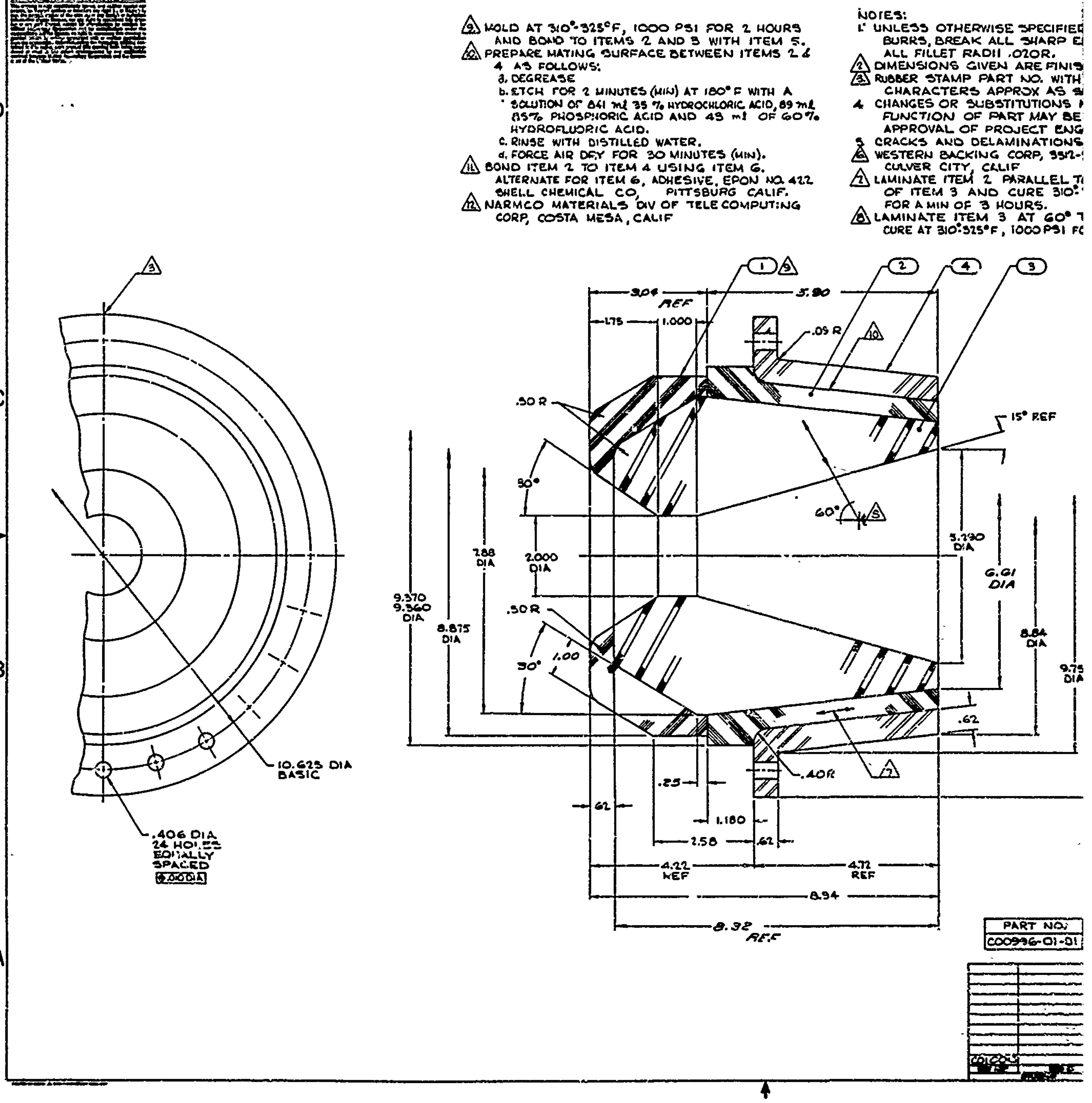
4. CHANGES OR SUBSTITUTIONS
FUNCTION OF PART MAY BE
APPROVAL OF PROJECT ENG[INEER]

5. CRACKS AND DELAMINATIONS

6 WESTERN BACKING CORP, 3512-
CULVER CITY, CALIF

7 LAMINATE ITEM 2 PARALLEL T[O]
OF ITEM 3 AND CURE 310°-
FOR A MIN OF 3 HOURS.

8 LAMINATE ITEM 3 AT 60° T[O]
CURE AT 310°-325°F, 1000 PSI F[OR]



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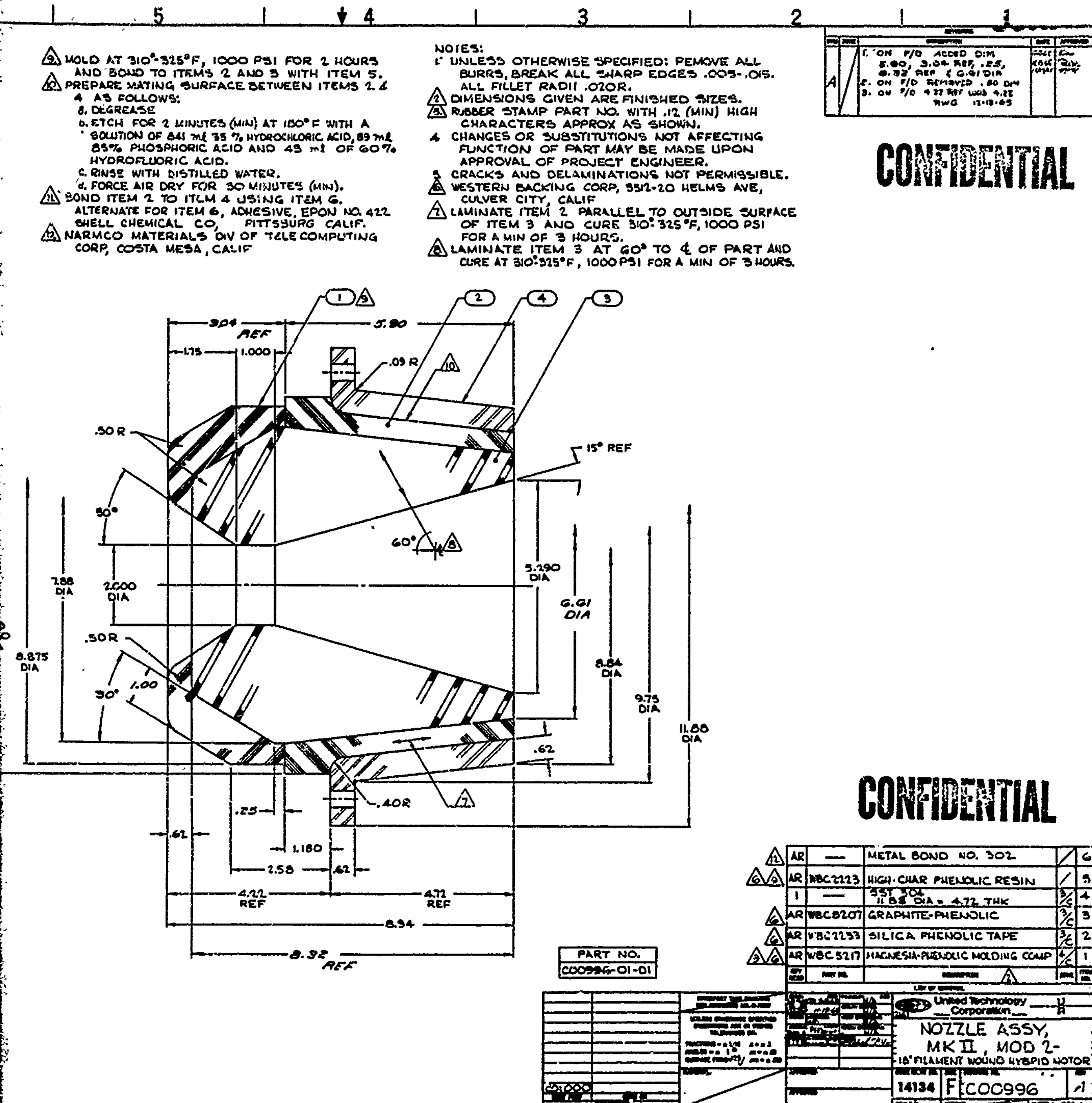

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Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) United Technology Center Division of United Aircraft Corporation Sunnyvale, California	2a. REPORT SECURITY CLASSIFICATION Confidential 2b. GROUP 4

3. REPORT TITLE

EXPERIMENTAL INVESTIGATION OF PREPACKAGED HYBRID PROPULSION SYSTEMS (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim Technical Summary for Period 1 April 1965 through 31 January 1966

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Vickland, C. W.

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An applied research and development program is being conducted on prepackaged hybrid propellant systems suitable for application to advanced tactical missile requirements. An 18-in.-diameter flight configuration hybrid motor has been designed, fabricated, and tested in three motor firings. A high density, high specific impulse hybrid propellant combination has been formulated, and a fuel grain has been developed which will provide nearly constant fuel flow rate and will permit nearly complete fuel utilization. Dual thrust injectors have been developed and successfully tested. A simple thrust control system has been designed, which will control the motor thrust at two levels and will permit multiple starts at either thrust level. The results of the program indicate that high density hybrid propulsion systems may be feasible for application to advanced tactical missiles. (U)

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
HYBRID ROCKET ENGINES						
HIGH DENSITY FUELS						
PREPACKAGED PROPULSION SYSTEMS						
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